New Views of the Moon II
Framework Chapter for Lunar Scientific Exploration

1.0 Introduction

Science activities conducted on the lunar surface will be the keystone for understanding the questions raised by the chapters in this volume. Executing these activities will be complex and expensive, regardless of whether the agent for conducting this research is human or robotic. Therefore, it is critical that each question be understood in the light of the assets necessary to acquire the appropriate data and the samples, the operations approaches necessary to conduct the surface science operations, and the preparations necessary prior to executing each mission. The premise of this chapter is that for each open question, there is a solution to acquiring the necessary data and samples that enhances efficiency, minimizes costs, and reduces the risk to human crewmembers. A pre-mission analysis of operational approaches appropriate to each question will identify the appropriate solutions, and so improve the chances of mission success.

Failure to analyze for the correct solution is likely to lead to a mismatch of mission assets with the scientific questions being investigated, leading to increased costs and increased risk. While this mismatch won't ensure mission failure, it can lead to mission costs that exceed budgets, or lead to development and deployment of assets that are either insufficient or overly sufficient to meet the science objectives of the mission. Further, the approach in this chapter assumes that with the exception of operating a large lunar outpost missions, each mission should avoid as much as possible multiple mission objectives and "piling on" mission requirements. In the past, unconstrained growth of mission objectives has led many missions to exceeding budgets and suffer subsequent cancellation. The best way to limit this possibility is to consider missions with single, straightforward mission objectives.

The two possible agents for surface science operations are humans and robots, either operating in isolation or in tandem. Each agent has both strong points and limitations, and neither agent is appropriate for all science operations tasks. Robots work best in the conduct of routine, repetitive activities, where the approach to solving a particular problem can be "formulaic" – robots do not get bored, do not tire as long as they have an active power system and can be counted on to repeat the same procedure identically as many times as they are called on. Also, the loss of robotic assets, while expensive, can be remedied with building and flying additional robots. While space flight has rarely been able to implement the economies of scale that have often been considered for robotic operations [**reference**], many of the science problems examined in this volume can be solved with repetitive simple science missions to multiple localities, rather than one large mission to a single surface locality.

Robots can be engineered to operate in environments that are hazardous to human explorers, although sometimes at considerable costs and significant launch mass. Robots, however, move very slowly in contrast to human planetary exploration vehicles, and at present, exploration of the lunar surface by robotic vehicles is likely to take considerably more time than human-operated vehicles. A comparison of traverse times between the Apollo Program and the Mars Exploration Rover (MER) is illustrative: it took the Apollo 17 crew three days to put the ≈29 km on the Lunar Roving Vehicle (LRV) odometer; it took MER Rover Opportunity over 3000

Martian sols to accumulate the same mileage [**reference**]. The relatively close proximity of the Moon will allow quicker cyclical robotic operations than can be executed on Mars, but nonetheless, it seems unlikely that robotic assets will be able to traverse the lunar surface with the speeds that can be achieved by human explorers.

In contrast to robots, human explorers are significantly better at developing exploration strategies and modifying those strategies in real time (Hodges and Schmitt, 2011). Hodges and Schmitt (2011) adapted the concept of flexicution [Klein, 2007a; Klein, 2007b] to illustrate how field geologic mapping is executed in a terrestrial setting, and should be applied to lunar scientific exploration as well. While not all lunar science problems require geologic mapping, developing a sufficient grasp of the geographic and stratigraphic setting of returned samples will be critical for answering many of the problems cited in this volume. Consequently, use of human explorers will always be a critical component of lunar surface exploration.

1.1 Previous Work [Eppler and Klaus preparation]

1.2 Mission Concepts

The concept of mission concept means matching open science questions with the capabilities needed, both for hardware and for crew, that will answer those questions. A critical part of this idea is that the level of hardware and human and robotic operations applied to a particular problem should match the operations needed to answer a particular question. Inadequate matching will result in either a mission that is insufficiently equipped to tackle a particular science operation, or has more expensive assets on the ground than are required to execute the science mission. For example, building up a data set of mare basalt ages and chemistries may need only a simple robotic sample return from the vicinity of a lander (a "smash-and-grab" mission), while sorting out the geology of a complex area, such as the Aristarchus Plateau, is likely to require extensive roving with pressurized rovers crewed by experienced field geologists with operating durations of weeks-months. Each concept carries with it linked requirements of vehicle development, operations approach and crew training so that the missions executed under that class are adequately performed.

1.2.1. Mission Concept 1

This involves either 1) simple sample return from a geographically-restricted area, or 2) deployment of a geophysical or environmental monitoring package. The basic concept involves landing a robotic spacecraft with dexterous manipulation capabilities but no mobility assets. In the case of a sample return, the spacecraft will sample <5 kg of material from the immediate vicinity of the lander, load the sample into a return capsule and launch that capsule back to Earth. This kind of mission could address geologic problems in localities that have simple field relations and largely require a suite of samples from the field area to answer critical questions. An example is establishing the first order petrologic variability and eruption age of the full suite of mare basalts defined by Hiesinger, et al., (2011). In this case, a basic small sample return will allow definition of each mare basalt province, and allow radiometric dating to correlate sample age with cratering statistics. In the case of geophysical or environmental monitoring, the spacecraft will have on board the necessary hardware and will have relatively simple deployment and activation requirements, capable of being handled by a dexterous manipulator.

1.2.2 Mission Concept 2

This involves detailed, mobile robotic characterization and sample return (≤5 kg) from a small but geologically complex area that needs more than a simple "reach and grab" sample return. In this case, the mission would be similar to an Apollo J-mission, but executed by a mobile, dexterous rover operated from the ground in a manner similar to the Mars Exploration Rover missions or the Mars Science Laboratory. The key difference between the cited Mars missions is that the spacecraft "base station" would have the capability to return samples.

This mission lends itself to relatively small (estimated to be <10 km^2) areas that have either anomalous geochemistry or landforms that suggest specific types of surface activity not common on the lunar surface. Some good examples are the anomalously high-Si regions of the Moon, such as Compton-Belkovich, or unusual areas of young volcanism, such as the putative vents in fractured floor craters (e.g., Alphonsus) or the Ina-D Caldera [**reference**]. Although individual mission operations would differ, the concept is to land the spacecraft near lunar dawn, operate the robotic rover for the lunar day, and return samples at the end of the ≈14 day mission. A key aspect of this concept is that depending on the nature of the returned samples and remote sensing data acquired during the surface operation, a Concept II mission could involve a follow-on exploration by human crewmembers.

1.2.3 Mission Concept 3

This mission is essentially an extended Apollo J-mission to a site that requires human crewmembers capabilities. These missions could deploy to either to a previously visited Concept II site or a new site, which requires human crew for a mission of ≤2 weeks. These sites are geologically complex, of high scientific value, and need more than robotic assets to characterize, but aren't large enough for multi-month duration mission with habitation and pressurized rover assets. Depending on the size of the site, it might involve up to 4 crew, unpressurized rover assets, a range of exploration out to ≈20 km, and up to ≈150 kg of sample return. An example of this concept would be an investigation of the basalt fill and lower slopes of the central massif in Tsiolkovsky Crater, characterizing both the mare basalts and the lunar crustal stratigraphy exposed in the central massif.

Although this is conceived of largely as a human crewed mission, depending on available downmass, it may be appropriate to carry to the surface robotic assets as well. Depending on the capabilities of these assets, they could extend the range of exploration or provide stay-behind assets to continue reconnaissance exploration. Further, although these missions are conceived of as single missions to areas of interest, it may be that a proposed location of a lunar base could also be investigated at a reconnaissance scale with the assets proposed here.

1.2.4 Mission Concept 4

This concept involves advanced exploration capability with semi-permanent habitation capability, multiple small pressurized rover assets, dexterous robotic rovers, deployed to characterize large, geologically-complex areas and/or conduct extended geologic reconnaissance roving missions. Two possible venues are the Aristarchus Plateau or South Pole-Aitken Basin, with long range roves such as envisioned by Cintala et al. (1985) and Kring and Durda (2012). The mission duration to these sites would be on the order of multiple months, with up to 4 crewmembers. Although this involve primarily siting at a single starting and ending location, it could also involve robotically deploying crew assets to a site where crew would land, conduct a long rove, and then return to the landed spacecraft for a return home. In both cases, this concept involves the most complex deployment hardware, the longest mission durations, and the highest cost. Consequently, these missions may not take place before extensive lunar surface reconnaissance.