Synopsis

Our examination of the scientific concepts and objectives in the NRC (2007) report *The Scientific Context for Exploration of the Moon* generated a series of requirements for surface targets that were then evaluated using a compilation of existing sample data and remote sensing observations. The latter were co-registered in an ArcGIS database and used to map locations where the requirements could be met.

The underlying question was, simply, where on the lunar surface could each of the NRC (2007) investigations be addressed? Rather than asking what could be accomplished at one place or another on the surface, the goal was to identify all locations on the lunar surface where each of the investigations could be addressed. Thus, this is truly a global assessment of the landing sites suitable for *The Scientific Context for Exploration of the Moon*.

That strategy produced several interesting results for each of the concepts. Moreover, by collating the results for each concept, the strategy has identified several sites on the lunar surface that are particularly science-rich targets. Some of them have not appeared in previous landing site assessments, even though they may be far better landing sites than those previously identified. For example, one of the sites that appeared repeatedly throughout the series of summer studies is the Schrödinger basin within the South Pole-Aitken basin on the lunar far side. At that location, the first and second highest priorities within the NRC (2007) report can be addressed, as can over half of the other scientific investigations in the report. It is an exceedingly fascinating location. Another interesting site is Amundsen crater, near the South Pole, which this study suggests is a better place to study polar volatiles than the often-discussed Shackleton crater.

In most cases, the missions require field work, sample collection, and return of those samples to Earth for analyses. In a few cases, measurements can be made in situ and/or must be made in situ (e.g., the geophysical network).

To address Concept 1 investigations, which involve the bombardment history of the Moon and its implications for planetary bodies throughout the inner solar system, samples need to be collected from a series of impact basins and craters that are distributed geographically around the Moon and are temporally representative of the collisional evolution of the Moon from the accretional epoch up to the present day. Those samples will need to be returned to Earth for analyses. The highest priority is to test the lunar cataclysm hypothesis, which means the magnitude and duration of the pulse of basin-forming events needs to be determined. The second highest priority investigation is to determine the age of the South Pole-Aitken basin. Both of those could potentially be addressed within Schrödinger basin, which is within the South Pole-Aitken basin and likely contains samples produced by both impact events. Because Schrödinger basin is the second youngest basin and SPA is the oldest basin, collecting samples from that location would virtually bracket the entire basin forming epoch. Moreover, other suites of rock available within Schrödinger basin can be used to address Concepts 3, 4, 5, 6, and 7.

Concept 2 investigations are designed to probe the lunar interior (lower crust, mantle, and core). Those issues can be addressed by both geophysical networks and sample return. While some progress can be made with the deployment of a single geophysical station, arrays of 4 to 8 globally distributed stations are needed to fully address the goals. The locations of those stations can (albeit not always) conflict with the locations of landing sites identified for the other concepts. Often, locations of geologic complexity where multiple types of terrains meet are the most attractive sites for other concepts. Terrain boundary locations, however, can be poor places for geophysical measurements like heat flow.

The investigations within Concept 3 are designed to use the diverse range of lithologies within the lunar crust to evaluate major planetary processes like planetary differentiation (e.g., the lunar magma ocean hypothesis). Multiple landing sites are generally required to fully evaluate crustal diversity and, in most cases, impact craters are used as probes of the crust. The team studying this concept high-graded their list of globally distributed sites and identified 14 impact craters that could provide a diverse sampling of the crust: Antoniadi, Aristarchus, Birkeland, Copernicus, Finsen, Jackson, King, Moscoviense, Orientale, Schrödinger, Theophilus, Tsiolkovsky, Tycho, and Vavilov. Specific landing sites were explored in

Aristarchus, Jackson, and Schrödinger. The team also noted that all five of the goals in this concept can be addressed within both Schrödinger and Orientale basins.

Unlike the other concepts, Concept 4 is geographically confined to a particular area of the Moon. In this case, five scientific goals were designed to study volatiles and their flux over geologic time in the polar regions. For the purposes of this study, the polar regions were defined as areas around each pole to a latitude of 80°. Maps of temperature, hydrogen abundance, slope, and permanently shadowed regions were integrated to locate the best areas to address each of the goals. The goal-specific maps were then integrated together to find those locations where all of the goals could be addressed simultaneously. Around the north pole, the total area was fairly large, but the sites were highly fragmented. That is, suitable sites were relatively small although many of them were scattered among the intercratered highlands. Larger sites exist around the South Pole. Specific landing sites in both the north and south polar regions were examined. Interestingly, Amundsen crater, located between Shackleton crater and Schrödinger basin, was a particularly attractive landing site. Robotic assets or crew could land in a sunlit area on the flat crater floor and then make short-duration excursions into the more challenging thermal and power environment of a permanently shadowed region.

Four science goals within Concept 5 use lunar volcanism to explore the chemical and thermal evolution of the lunar interior. Volcanic processes resurfaced 17% of the Moon (~33% of the nearside and ~3% of the farside). Suitable landing sites to address these goals were again mapped globally. Some sites are sufficiently diverse that they can provide access to samples that address multiple goals. Ten sites were identified that might provide the greatest insights: Montes Harbinger, Oppenheimer, Marius Hills, Apennine Bench region, Lomonosov-Fleming region, Gruithuisen Domes, Mare Moscoviense, Aristarchus Plateau, Mairan Domes, and Mare Smythii.

Concept 6 recognizes that the Moon has an extraordinary record of impact cratering processes and is, thus, the best place to study those processes in the Solar System. Lessons learned on the Moon could then be applied to the Earth and all other planetary surfaces. Several very well preserved impact sites of different sizes and morphologies would need to be targeted. For example, a Copernican-age central peak complex crater like Tycho, Copernicus, King, or Jackson craters should be explored. A good transitional structure would be Antoniadi crater. Schrödinger is the best preserved small basin and Orientale the best preserved large basin. Orientale was evaluated in more detail and several landing sites were proposed to answer different goals within Concept 6. In one case, a pair of landing sites in the eastern margins of the basin (and on the nearside) were identified to test models of basin formation. The team also realized, however, that a landing site in the northern part of the inner basin, near where Maunder crater excavated some of the deeper Orientale lithologies, provides an opportunity to simultaneously address all of the goals in this concept.

The regolith of the Moon, which may provide insights applicable to all airless bodies, is the focus of Concept 7. In general, this concept and its four goals are not important drivers for landing site selection. We can study lunar regolith properties everywhere on the Moon. Nonetheless, if one wants to fine-tune missions to address specific issues, there are places that may be more informative. The most interesting sites are those that have never been explored and those with diverse types of regolith. Potential landing sites in Mare Moscoviense and on the ejecta blanket of Tycho crater were examined in greater detail.

As noted in the preface, this study did not include Concept 8, which involves measures of the atmosphere and dust environment while it is still pristine (i.e., before significant surface operations begin). Those issues are going to be addressed by the LADEE mission.

One of our teams examined, instead, the immense 2,500 km diameter South Pole-Aitken basin and evaluated which of the Concept 1, 2, 3, 4, 5, 6, and 7 goals could be addressed within its margins. Interestingly, this study found that one can begin to address most of the science goals in the NRC (2007) within the South Pole-Aitken basin. In some cases, surface activities within South Pole-Aitken can significantly resolve the NRC (2007) science goals. This study was also being conducted with input from an OSWEG (Optimizing Science and Exploration Working Group) study and a LEAG (Lunar Exploration Analysis Group) Science Scenarios for Human Exploration Specific Action Team (SAT) report. The OSWEG and LEAG-SAT groups were considering an architecture with assets delivered to the South Pole near Shackleton crater. Those assets could then be deployed and used by crew within distances of either 500 km or 1000 km. Sortie missions to locations at greater distances were also possible. Schrödinger is the

most attractive science exploration site within the 500 km limit. If mobility was extended to 1000 km, then Antoniadi crater would be another attractive site. Beyond that limit, but still within South Pole-Aitken basin, Van Karman crater is a good target. In all three cases (Schrödinger, Antoniadi, and van Karman), multiple goals in multiple concepts can be addressed. And, even if the OSWEG architecture is not used, these three sites are still very attractive science and exploration targets.

As this study unfolded, it became clear that the Apollo landing sites, while provocative and having completely re-shaped our vision of solar system processes 50 years ago, represent only a tiny fraction of the lunar surface. Other sites can reveal completely new details of lunar history and are, arguably, better sites for addressing the fundamentally important issues identified in the NRC (2007) report *The Scientific Context for Exploration of the Moon*.

The Moon is still largely unexplored. The work captured here will hopefully point mission planners to the most productive science and exploration sites on the Moon. We are ready to get back on the surface of the Moon and spark another era of discovery.