FORMULATION, MODELING AND ANALYSIS OF A MISSION TO THE MOON'S MALAPERT MOUNTAIN.

Charles R. Weisbin[1], Pamela Clark[2], Kacie Shelton[1], Jeffrey H. Smith[1], Joseph Mrozinski[1], William Lincoln[1], Alberto Elfes[1], Hook Hua[1], Virgil Adumitroaie[1], Robert Silberg[1]; [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109; [2]Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, Maryland 20771. E-mail: Charles.R.Weisbin@jpl.nasa.gov

Introduction: NASA's program for human return to the Moon incorporates several major themes, including science activities, preparation for crewed missions to Mars, and extending human presence on the Moon to enable eventual human settlement [1]. To a considerable extent, these themes are complementary, but the themes and the relative emphasis of specialized subsets of interest within them also compete for limited budgets and resources, requiring the formulation of alternative mission architectures and a comprehensive system for choosing among them. The selected architectures, in turn, require investments in technologies to provide the requisite capabilities. This study develops and analyzes a proposed exploration mission to the Moon's Malapert Mountain. It employs a systems-engineering tool enabling an objective, thorough, and traceable exploration of the trade space to maximize productivity in making these selections.

Case Study: The hypothetical mission takes a group of astronauts and their robotic assistants from a landing site at Shackleton crater near the lunar south pole to Malapert Mountain, which is about 130 km away, and back again. Malapert Mountain is a most attractive candidate for field work from Shackleton because of its potential scientific interest as a structural rampart of an outer ring of South Pole Aitken Basin and because of its suitability as a science-package deployment site. Its peak is favored with very long periods of sunlight and thus offers an excellent location for solar-electric power generation [2]. Its altitude may enable line-of-sight communications and power-beaming to sites across the region, including the rim of Shackleton crater. Earth remains visible at the mountain's peak, enabling a direct communications link. And finally, a nearby crater is thought to be a possible "cold trap" containing water ice in its permanently shadowed areas. Greatly improved topography data available over the course of the next year will be scrutinized to find passable routes up the mountain's relatively steep slopes.

En route to and from the mountain, the agents stop at a total of 11 localities at Shackleton crater, Shoemaker crater, and Malapert crater to conduct experiments designed to gather information relating to 3 major science objectives: the lunar basin's structure, the Moon's history (and by extension, Earth's history) of bombardment by meteorites and comets, and the potential for in situ water and hydrogen (see Figure 1). With travel to the various science-activity stops, the round-trip journey totals about 350 km.

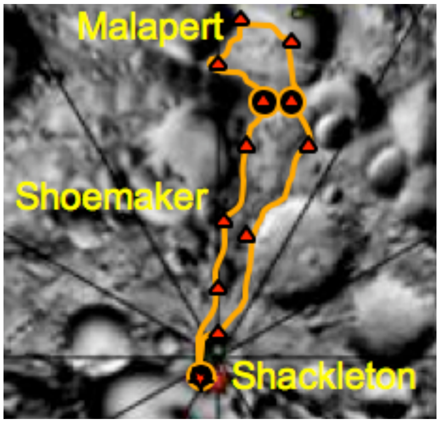

Figure 1: Possible exploration route from Shackleton to Shoemaker to Malapert Mountain and back. Major stops are marked by a triangle, camping sites by a black circle.

At these stops, a number of science activities are conducted. Representative samples are given in Table 1 below.

Science Activity	Illustrative Weight	Estimated Time
Geochemical mapping	10	On while rover moving
Ground-penetrating-radar mapping	10	On while rover moving
Rock sampling	10	2 min/sample
Regolith sampling	10	2 min/sample
Seismic measurements: Geophones	6	45 minutes (2 astronauts)
Subsurface drilling	3	30 minutes (2-meter depth)
Deploy environmental package	8	3 hours (2 astronauts)
Deploy geophysical package	8	3 hours (2 astronauts)

Table 1: Illustrative subset of science activities conducted during hypothetical mission.

Analysis Approach: This study employs an analysis approach which combines the best features of two analytic techniques to overcome difficulties of combinatorial explosiveness of the trade space. Further, this approach produces an optimized scenario in which "as much science as possible" is conducted, in contrast to approaches that use a prescribed set of experiments which may either not fit into all of the available time slots or may not fully utilize all of the time slots, leaving unproductive time remaining.

The HURON (Human-Robot Optimization Network) system and its associated sensitivity-analysis capability has been successfully employed by JPL's START (STrategic Assessment of Risk and Technology) team in several studies of human-robot interaction on the Moon [3–5]. HURON uses the A* algorithm, which is commonly used for searching state-space graphs. Given a set of constraints and an objective function (e.g., maximize productivity in terms of benefit divided by cost), HURON is able to search a trade space to allocate tasks among available agents—both human and robotic—and to calculate a schedule detailing which agent is doing what at any given moment in an optimal scenario.

A complementary optimization system called SciMax (for Scientific Maximization) [6] is deployed in conjunction with HURON. The SciMax integer programming approach is more approximate than HURON; it cannot produce a detailed schedule of activities or calculate an optimal allocation of tasks to agents. It is able, however, to calculate an optimal route for agents that need to travel to multiple sites within the bounds of specified constraints, and to calculate how much time is available for science at each location. It achieves the latter by subtracting all non-science activities (e.g., driving between sites) from the total available time and applying an input "science policy," such as "time is to be divided equally among all sites," or "more distant sites are to be awarded more time." Importantly, it is able to perform its calculations within seconds.

Our integrated approach uses SciMax to do route selection and to define the amount of time available for science activities at each site, and then uses HURON to fill each block of time with an optimized package of science activities and, if desired, to allocate the tasks to the available agents. The integrated approach is extremely rapid and permits dynamic replanning conditioned on observing an unexpected discovery; an example of this is given in the presentation.

Weighting of individual science goals lead to different sets of scientific investigations and different amounts of time to be spent at the various sites. We develop tables similar to Table 1 for each of the three major science objectives.

Our analysis results include the following:

1. Optimal selection of experiments for each of three different science objectives (the time available at each site is highly constrained and experiment selection is critical).
    a. Type, sequence and number of experiments desired and actualized, depending upon science focus and time constraints.
2. A comprehensive sensitivity analysis in which the most important parameter uncertainties are considered.
3. Figure of merit for overall productivity, and relative productivity across each science goal.

Implications for Field Science: This effort allows study of the implications for supporting science activities at the level of the "real" science, including field-experiment design and field-activity planning. We consider whether the needs of such activities can be adequately met with existing architecture in order not only to "sample" an observable outcrop but also to provide context to interpret sample measurements. We also consider the optimal use of robotics with humans in the loop.

References: [1] Lunar Exploration Analysis Group (LEAG) chaired by Clive Neal for NASA HQ, see http://www.lpi.usra.edu/leag/meetings.shtml. [2] Schrunk, D.; Sharpe, B.; Cooper, B.; Thangavelu, M.; (2007) "The Moon: Resources, Future Development and Settlement," page 84. [3] Weisbin, C. R.; Mrozinski, J.; Lincoln, W.; Elfes, A.; Shelton, K.; Hua, H.; Smith, J. H.; Adumitroaie, V.; Silberg, R.; "Lunar Architecture and Technology Analysis Driven by Lunar Science Scenarios," submitted to Systems Engineering Journal, November 2008; [4] Weisbin, C. R.; Mrozinski, J.; Hua, H.; Shelton, K.; Smith, J. H.; Elfes, A.; Lincoln, W.; Adumitroaie, V.; Silberg, R.; (2008) "Human-Robot Lunar Exploration: Pressurized vs. Unpressurized Rovers," Proceedings of the 19th International Conference on System Engineering, 8–12, University of Nevada, Las Vegas, USA. [5] Hua, H.; Mrozinski, J.; Shelton, K.; Elfes, A.; Smith, J.; Lincoln, W.; Weisbin, C. R.; Adumitroaie, V.; (2008) "Analyzing Lunar Mission Architectures Using An Activity Planner for Optimizing Lunar Surface Human-Robot Operations," Conference on System Engineering Research, Los Angeles, CA. [6] Smith, J. H.; Weisbin, C.; Elfes, A.; Lincoln, W.; Mrozinski, J.; Shelton, K.; Hua, H.; and Adumitroaie, V.; (2009) "Human and Robot Task Allocation: An Operations Management Approach for Work-System Productivity," accepted for presentation/proceedings of the 38th Annual Meeting of the Western Decision Sciences Institute, Hilton Kauai Beach Resort, Kauai, HI; April 7-11, 2009.