Lunar Polar Prospecting Workshop: Findings and Recommendations

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Table of Contents

Acknowledgements

This report was prepared by Gareth Morris and George Sowers. It was reviewed by Chris Dreyer, Angel Abbud-Madrid, Sam Lawrence, and Clive Neal.

1.0 Executive Summary

The Lunar Polar Prospecting Workshop was conducted on June 14 and 15, 2018 at the Colorado School of Mines in Golden, Colorado. It was held in conjunction with the 19th Space Resources Roundtable. The workshop was sponsored by the Space Resources Roundtable and the Lunar Exploration Analysis Group (LEAG). The evening reception was sponsored by United Launch Alliance (ULA). There was a diverse participation of individuals from academia, government, and industry and many constructive discussions took place. This report documents the proceedings, findings, and recommendations of the workshop.

The purpose of the workshop was to develop a roadmap for a resource exploration campaign focused on ice deposits at the lunar poles that could lead to industrial scale production of LO_2/LH_2 propellants within ten years. A business case analysis indicates that the availability of lunar propellant can dramatically decrease the costs of transportation beyond low Earth orbit, dramatically decreasing the cost of NASA's Moon and Mars exploration programs and jump starting commercial activity in cislunar space.

The first step in developing lunar ice resources for propellant production is characterizing the resource to the extent that it can be regarded as a proven reserve. See the LEAG Lunar Exploration Roadmap implementation plan (Shearer, 2011). This process is well understood for terrestrial resources and those proven processes were the starting point for the workshop. This entails detailed resource mapping as well as identification of economical extraction and processing methods.

The workshop resulted in six findings and six recommendations. The findings are:

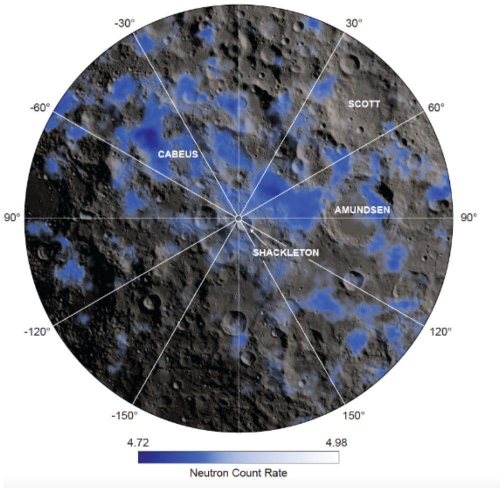
1. *Use of the term prospecting should be avoided. The process to definitively characterize a space resource such that it becomes a proven reserve should be referred to as space resource exploration.*
2. *The lunar mining strategic knowledge gaps (SKGs) proposed at this workshop provide a useful guide in developing a space resource exploration campaign.*
3. *The combination of the LRO and other lunar orbiting spacecraft have provided a solid foundation of remote sensing data of the lunar poles. However, the resolution of the data is insufficient to meet the mining SKGs (10-20 km resolution for neutron data [H detection] versus <100 m required). In addition, proper interpretation of existing and future remote sensing data requires ground truth; i.e. direct confirmation of surface and subsurface conditions corresponding to a particular remote sensing signature.*
4. *The use of large numbers of mass-produced, low-cost exploration devices will greatly enhance the cost effectiveness of the lunar resource exploration campaign.*
5. *Resource exploration must be viewed as an orchestrated campaign, not a set of independent missions. Each mission in the campaign builds off the ones before and provides a foundation for the ones that come later. However, given financial and time constraints, there is great value in rapid and parallel operations in mission development and execution.*
6. *Any use of high cost, complex rovers should be minimized and employed only as a final verification in a location where there is high confidence an economically viable resource exists.*

The recommendations are:

1. *The first priority for the lunar ice exploration campaign is to obtain ground truth in one or two key locations. This can be obtained by a lander equipped with a drill and other instruments to detect volatile species. Data from this mission will be used to anchor geologic models of the nature and formation of the lunar poles and their ice deposits. The data will also be used to calibrate existing remote sensing data for use in site selection for follow-on missions.*
2. *Geologic models and resource maps should be developed, then refined throughout the exploration campaign.*
3. *In parallel with the ground truth landers, a cubesat swarm should be employed to gather high resolution remote sensing data at the lunar poles relevant to the existence and characterization of water. The cubesats should fly as low as possible (10-20 km above the surface). The same mission should also deploy a swarm of hundreds of low cost impactors instrumented for volatile detection and quantification.*
4. *Based on the previous results, a small number of the most promising locations should be selected. For each location, a small lander will be deployed. Each lander is equipped with a number of deployable, tethered sensor packages.*
5. *Based on the previous results, and if a sufficiently high probability location(s) has been found, a rover/sampler mission should be sent to that location for detailed resource mapping and verification of economic viability. This mission should include an ice extraction technology demonstration. Power options for this mission, which will require long duration operations within the PSR, include an RTG and a separate power beaming lander in an adjacent sunlit region with view into the PSR.*
6. *NASA should direct the LEAG to convene a Specific Action Team (SAT) to develop the details of the lunar polar ice exploration roadmap sufficient to begin mission planning.*

2.0 Introduction

One of the first economically viable uses of resources in cislunar space will be propellant from water. There are several reasons for this. First, one of the most significant findings of space science of the last decades has been the abundance of water in the inner Solar System. The permanently shadowed regions (PSRs) near the poles of the Moon harbor significant quantities of water in the form of ice. Figure 1 is an image of the lunar south pole. Indicated is the Cabeus crater where a spent Centaur upper stage was crashed to examine the spectral content of the ejecta plume. Water content measured in the 5–10 wt% range. Water's constituents, oxygen and hydrogen, when separated and liquified, are the most efficient chemical rocket propellants known. Finally, space-sourced propellants can dramatically reduce the cost of every other activity in cislunar space. Table 1 provides some examples.



Credit: NASA/GSFC/SVS/Pockocmoc

Figure 1. *Neutron count of the South Lunar Pole, an indication of water.*

Table 1. *Benefits of space-sourced propellants.*

Cislunar Activity	**Space-Sourced Propellant Benefit**
Transportation from Earth to Geosynchronous orbit	10-20% lower cost
Transportation from Earth to Lunar surface	70% lower cost
Cost of a human mission to Mars	2-3 times reduction
In-space transportation	Essentially the cost of space-sourced propellant

Market demand for propellant in cislunar space already exists. United Launch Alliance (ULA) publicly set a price for propellant delivered to various places in cislunar space (Sowers 2016). The price ULA is willing to pay on the surface of the Moon is $500/kg for 1100 mT of propellant per year. To address this need, the Colorado School of Mines recently developed system level concepts for a mining operation within a PSR (Dreyer et. al. 2018). All the concepts indicated that the price target is feasible. One concept showed a potential to better the target by more than 25%. In addition, NASA has indicated a need for 100 mT of propellant per year on the lunar surface to fuel ascent vehicles. Business case analysis shows favorable returns for both commercial and government investment.

The key assumption is that ice exists at the lunar poles in sufficient quantities and in a form that allows for economical extraction and processing. The indications are favorable, but the uncertainty is great, far greater than what an investor would require to risk the billions of dollars required to emplace the necessary infrastructure. On Earth, the activities to locate and assess mineral resources historically have been called prospecting. The modern systematic process to identify, map and assess resources is called resource exploration. (See Finding 1.)

The Lunar Polar Prospecting Workshop was conceived with the idea of creating a roadmap for a lunar polar resource exploration campaign to inform commercial and government decision makers as plans are formulated for future lunar exploration missions.

3.0 Overview

The Lunar Polar Prospecting (LPP) workshop was held directly after the ninth joint Space Resources Roundtable (SRR) and Planetary & Terrestrial Mining Sciences Symposium at the Colorado School of Mines in Golden, Colorado on June 14-15, 2018. Its aim was to bring together the diverse attendees of the SRR and build a roadmap for a Lunar Polar Prospecting campaign that could lead to industrial scale production of water/propellant within a decade. Once collated and structured, this roadmap will be disseminated to space agencies, commercial companies and academic institutions interested in developing lunar water/propellant resources.

The incremental goals of this type of workshop were laid out by George Sowers in the workshop introduction, with the final goal being the establishment of a permanent human presence in space. This starts with exploration for resources to set up lunar ice mines and refineries to turn ice into propellant that would dramatically lower the cost for all other activities. Once an extra-terrestrial propellant industry is established the economic engine of the free market will provide growth, expansion and innovation. This will lead to a growing cislunar economy that brings the resources of the solar system within the economic sphere of humankind. However, we are still very early on in this journey and the LPP was aimed at beginning to unify the disparate industries required to take advantage of this not-so-new frontier.

The attendees were initially split into 9 teams with the overall aim of developing a series of missions that would:

- Close the proposed strategic knowledge gaps (SKGs) preventing lunar ice mining
- Achieving the required knowledge state to enable industrial scale ice mining and propellant production within the decade.

To promote discussion a short series of talks were given by the organizers, covering several of the prominent areas that need to be addressed. These are listed below and are summarized in the following several pages:

1. State of knowledge of Lunar Polar Ice and Volatiles – Clive R. Neal, University of Notre Dame
2. Lunar Ice Mining Strategic Knowledge Gaps – George Sowers, Colorado School of Mines
3. Summary of Prospecting Technologies – Chris Dreyer, Colorado School of Mines
4. LEAG Lunar Exploration Roadmap - Clive R. Neal, University of Notre Dame
5. LPP Team instructions – George Sowers, Colorado School of Mines

4.0 Presentation Summaries

Summaries of the introductory presentations are included below. The presentations are included in Appendix A.

4.1 State of Knowledge of Lunar Polar Ice and Volatiles – Clive R. Neal, University of Notre Dame

The presence and abundance of water on the moon

The presence of trapped water and other volatiles at the Lunar poles was first proposed by Watson et al. (1961) and was further developed by Arnold (1979). Analysis of Lunar Prospector data by a range of authors (Feldman et al. 1998, Lawrence et al. 2006 and Elphic et al. 2007) helped build the case further, with hydrogen being identified in the permanent shadowed regions (PSRs) at both poles (Lawrence et al. 2006).

The Lunar Reconnaissance Orbiter was launched in June 2009 as an Exploration mission with seven instruments specifically selected to provide datasets enabling human lunar exploration, including providing the information necessary to guide future utilization of lunar resources. The co-launched Lunar Crater Observation and Sensing Satellite (LCROSS) and its Centaur upper stage impacted the South Pole on the 9th October 2009 and LCROSS analyses of the plume ejected by the Centaur yielded estimates of the H_2O concentration at 5.6 +/- 2.9 wt%, along with many other potentially useful volatile species (Colaprete et al., 2010, 2012).

In addition, measurement of the albedo of the PSRs shows them to be more reflective than polar surfaces that are sometimes illuminated. While the cause of this cannot be known for sure with present orbital datasets, two possible explanations are water frost on the surface of the PSRs and a reduction in the effectiveness of space weathering in the PSRs. The Shackleton crater is the most reflective in its size range and models predict between 3-14 wt% water ice. (Lucey et al., 2014, Fisher et al. 2017)

Mini-RF scanning shows up radar circular polarization (CPR) and has been used by Spudis et al. (2013) to identify anomalous high-CPR craters, indicating possible water ice. These craters tend to be congruent with areas of known elevated H abundancies (Figure 2).

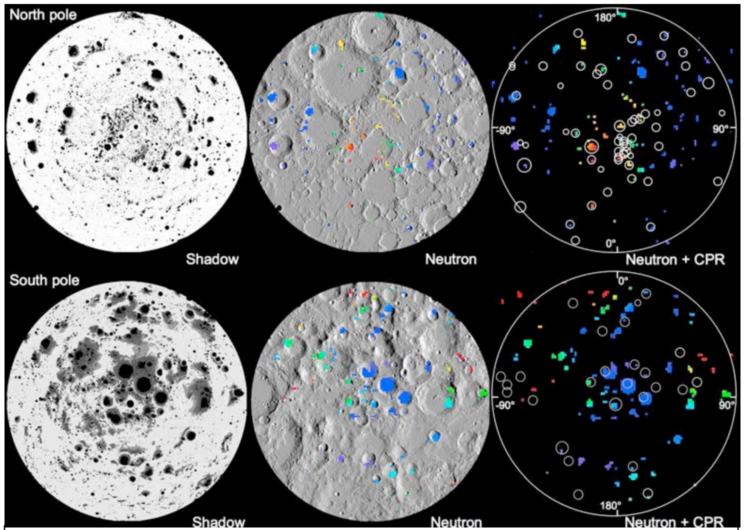


Figure 2. *Spudis et al (2013).*

In addition, Sanin et al. (2017) converted neutron count data to ‘water-equivalent-H’ in the top ~1m of the regolith. Their estimates came in at up to 0.55 wt.% water. Therefore, there is a wide range of estimates for the amount of water available in any given place near the lunar poles, from ~0.1-14 wt.%. However, the consensus assessment of the science community is that water exists in the lunar polar regions in some quantity. The challenge is to now identify a location that is economically and technical feasible to develop.

Using orbital data to plan lunar polar surface exploration

The South and North poles have similar environments with hydrogen >150ppm and average temperature <110K. Both polar regions also have large areas where LRO data has shown that the morphometry of the environment makes it completely feasible for spacecraft to land and rove, with adequate sunlight available in both locations. Excellent candidates for early exploration missions are the Cabeus and Shoemaker/Nobile vicinities in the South Pole and the Peary vicinity in the North, as all these areas also have some form of Earth visibility to enable convenient communication.

While the PSRs are currently thought to be the most promising locations for economic resources to be developed, both the PSRs and their surrounding areas should be surveyed. If it is not necessary to enter a PSR, developing the resources becomes cheaper as fewer RTG powered rovers will be required. The Resource Prospector mission effort showed that solar powered rovers can last multiple day-night cycles at the lunar poles in sunlit regions.

In depth surveys of the lunar surface will allow a much more detailed picture to be developed including the 3D distribution of the deposits, their form and composition as well as quantifying the geotechnical properties of the regolith. All of this is required to assess the ease of extractability as well as quantify the refining process and logistics required to operate a successful lunar fuel refinery.

The problem of prospecting a sufficient area to evaluate the resource with the minimum expenditure has been worked by the mining industry for some time. The RP team has developed a Monte Carlo based modelling approach to test the uncertainty in sampling patterns and resolution versus a defined ore body. Re-purposing this model for the lunar environment comes with risks as the mineral model is less well understood but it outputs a minimum traverse required of 180 m within a given prospect, fixing the goal traverse distance for a rover at 320 m.

Summary

Space transport requires fuel and the Moon is known to have resources—both at the poles, and other locations globally, such as pyroclastic deposits—that can be used to produce it. It is necessary to understand if the polar resources are reserves and therefore able to be economically developed. It is important to note that at the lunar poles, is the resource that is being prospected for, so oxygen and hydrogen will be the fuels derived. While some engines in development are LO_2-Methane, several companies are pursuing space transportation architectures based on LO_2/LH_2 propulsion. Examples include United Launch Alliance (ULA) and Blue Origin.

4.2 Lunar Ice Mining Strategic Knowledge Gaps – George Sowers, Colorado School of Mines

Mining Strategic Knowledge Gaps (SKGs). As proposed at the workshop, represent the totality of geologic and geographic information necessary to characterize lunar ice as a proven reserve of sufficient value to close the business case. This includes the location and grade of ice deposits, the physical characterization of icy regolith, and the geographical operational considerations. The geo/ops considerations include, but are not limited to: proximity to sunlit areas; sites for propellant processing and landing/launch pads; and suitability of surface for transport vehicles.

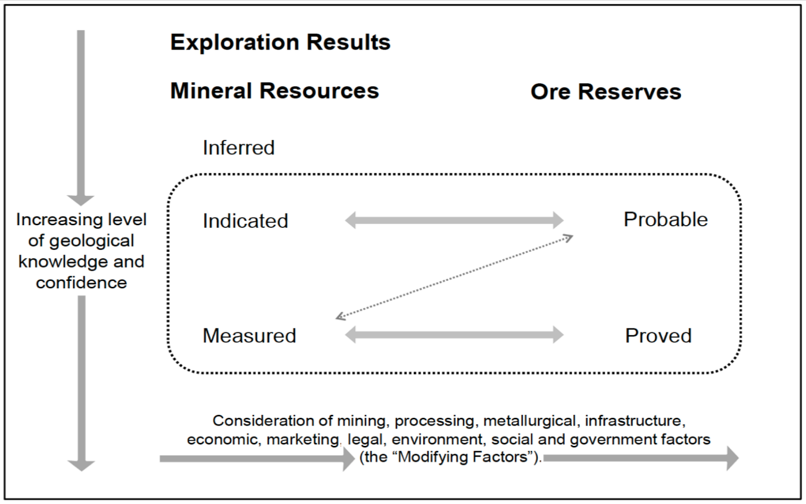


Figure 3. *Framework to develop a mineral resource. JORC 2012.*

Figure 3 shows the levels of knowledge required to develop a known reserve and prove it out as a resource in terrestrial mining. Many of the mining sector existing methodology and terminology will need to be borrowed to describe and successfully communicate the technology and knowledge gaps required to successfully develop ISRU.

When developing the case for lunar ISRU, specifically the mining and refinement of polar water for LO_2/LH_2 fuel, there are a few ground rules and assumptions that have been taken for the workshop. The first is that the reference business case used is the one that has been developed by ULA and CSM (Sowers, 2016; Sowers 2018; Dreyer et. al., 2018). The second is that the mining approaches to be considered are those developed by CSM in 2017 and refined further at ULA sponsored workshops. These are split into three approaches:

- Excavation and bulk heating of icy regolith
- Subsurface in-situ heating and vapor collection
- Surface in-situ heating and vapor collection

In addition, it is assumed that, if effective, the in-situ heating methods will be lower cost and more robust than the alternatives.

The anatomy of the theorized lunar ice mine is that it will likely be located in a permanently shadowed region (PSR) with power supplied by nearby permanently sunlit regions. There are, of course, options for the use of nuclear power in the PSR. The operation of the facility and machines is autonomous, or teleoperated. Ice will be extracted at the ice field then transported to the processing facility for purification and refinement. The processing facility itself is assumed to be near the landing/launch pad and acts as a centralized LO_2/LH_2 propellant refinery. The overall schematic is presented in Figure 4.

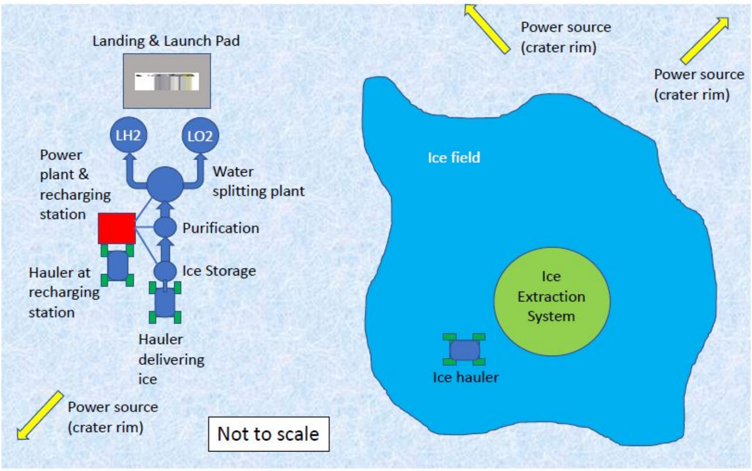


***Figure 4.** Generic lunar ice mining architecture.*

Building from the ULA/CSM plans, the propellant production rate is the defining factor that determines the required grade of an economically viable deposit. This has developed over time, starting at 1100 mT/yr of propellant in the original ULA business case (Sowers, 2016), through 1200 mT/yr in the Sowers PPP business case in 2018 and most recently revised upward again to 1500 mT/yr, which is the current value after the most recent ULA workshop held in March 2018.

To supply a given mass of propellant, a mass of ice 1.54 times greater must be mined, based on a propellant mixture ratio of 5.5 LO_2 to LH_2 by mass. This means that 1700 to 2300 mT of ice per year need to be mined from a chosen deposit (or deposits within transport distance to the refinery). With a ten-year assumed mine lifetime, and rounding up, a viable deposit must therefore contain at least 25,000 mT of extractable ice.

The concentration of ice by mass has a large effect on the energy required to sublimate and extract it. Any regolith with a concentration above 4% by weight becomes markedly less energy intensive to process as shown in Figure 5.

However, while LCROSS data suggests that there may be a concentration of around 5% by weight, at least in Cabeus crater, and while this is not thoroughly validated, it is promising. The actual grade of the icy regolith will have an understandably large impact on the viability of the resource. The physical structure of the icy regolith (dirty snow, frozen concrete, some other form) will also impact operation. This is a key SKG.

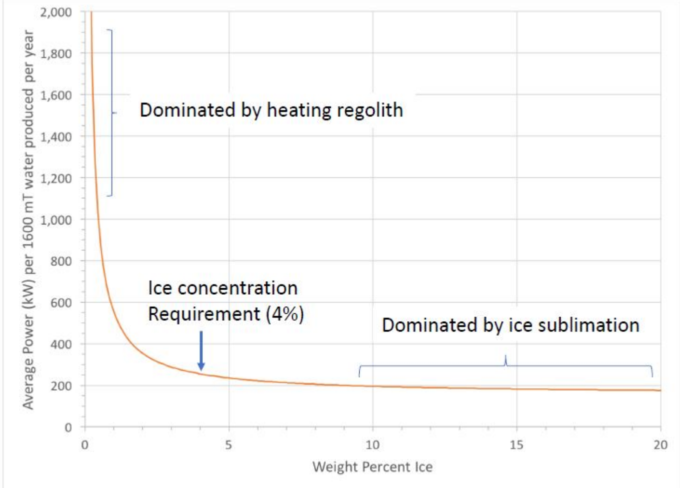


***Figure 5.** The energy required to sublimate ice versus wt% ice within the regolith.*

Other important parameters that need to be considered for the development of a mining plan can be split into three categories: relevant to all methods, relevant to in-situ heating, and relevant to excavation. They are detailed below.

Key parameters for all methods

These include the presence and amounts of other volatiles that will contaminate the water that is extracted. In addition, the heat capacities of the regolith to be processed are also important. Finally, the depth-wise distribution of the ice is required to size the operation.

Key parameters for in-situ heating

These are more material based, including the porosity and thermal and electrical conductivity of the deposit.

Key parameters for the excavation methods

These include the basic geotechnical properties of the deposit, including strength, ductility and hardness as well as the geotechnical properties of the bulk material.

Finally, the electrostatic forces that the dust and bulk regolith will be subject to will require some analysis. This force, while poorly understood, has large impacts on the behavior of fine, charged material such as regolith, especially when large amounts are moved around.

Operational considerations for an identified and economically viable deposit become more traditional with considerations for transport, proximity to power (sunlit regions) and freedom from major obstruction (boulders), all affecting the suitability of a given site.

4.3 Summary of Prospecting Technologies – Chris Dreyer, Colorado School of Mines

In the search for an economically exploitable resource one needs to find the solid material in question in a concentration of such form, grade and quantity that there are reasonable prospects for eventual economic extraction (Figure 3). In order to gather enough information to understand this fact, a prospecting plan needs to be drawn up taking samples in an organized pattern to interpret the data and interpolate possible subsurface deposit structures (Figure 6).

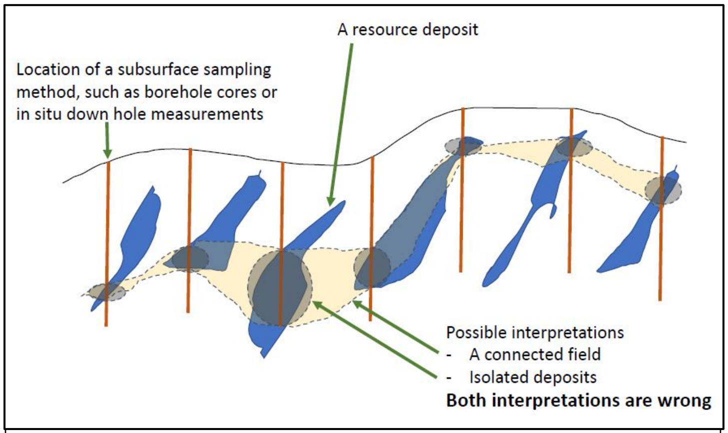


Figure 6. *Possible resource deposit structures and interpretations based on sampling method.*

Both new and existing technologies can be used for lunar mineral exploration and prospecting, and will encompass measurements taken from orbit, by landers and by rover or hoppers. In addition, there are a large number of ways of taking samples, including those that sample through direct contact (drilling) and remotely (spectral imaging).

An instrument used to measure a sample property remotely can operate in one of the ways depicted in Figure 7.

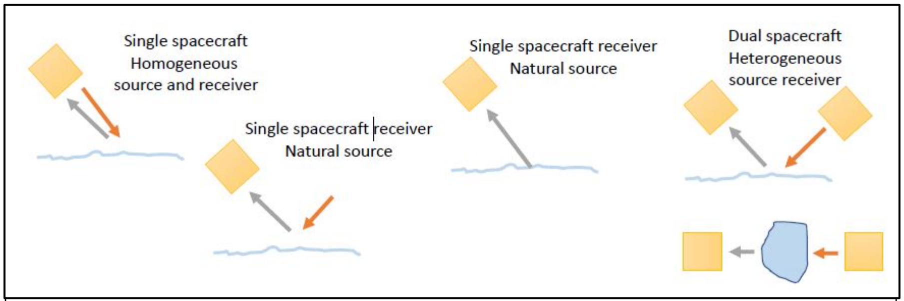


Figure 7. *Instrumentation categories for resources exploration.*

Previous missions to the Moon have used a wide range of methods to measure the surface properties, including radar, thermal imaging, visible imaging, visible imaging, laser altimetry, neutron spectroscopy, and visible/near-infrared spectroscopy.

The recently cancelled Resource Prospector mission had a wide variety of sampling probes including cameras, a neutron spectrometer, a near infrared (NIR) volatiles spectrometer system, a sampling drill, and processing and analysis tools to try out prospective technologies for volatile extraction.

Many sensing methods do not penetrate the surface very deeply—on the order of microns—therefore subsurface characterization techniques are required sufficient to study up to 1 m beneath the surface. These include drilling for core analysis, synthetic aperture radar, ground penetrating radar, and active seismic imaging. All of these techniques ultimately need to increase the spatial resolution of the possible deposit and identify its bulk characteristics.

4.4 LEAG Lunar Exploration Roadmap – Clive R. Neal, University of Notre Dame

It is important to learn from the history of space exploration; Apollo style sortie missions are not sustainable. Establishing a sustained lunar exploration program requires clear United States focus on lunar surface activity, international collaboration, ISRU, and commercial sector involvement. The LEAG is at the center of integrating such efforts, it serves as a community based, interdisciplinary forum for future science and exploration. Three themes have been developed from the question 'Why should we go to the Moon?' encompassing a science theme, a feed forward theme and a sustainability theme, detailed below.

Science (Sci) Theme

Pursue scientific activities to address fundamental questions about the solar system, the universe and humanity's place in them.

Feed (FF) Forward Theme

Use the Moon to prepare for future missions to Mars and other destinations.

Sustainability (Sust) Theme

Extend sustained human presence to the Moon to enable eventual settlement.

Each of these themes has a flow that allows it to derive feasible projects. From the theme a set of goals are set out, which are then broken down into objectives. Finally, these objectives are used to define a series of investigations (for the Sci and FF themes) and initiatives (for the Sust theme) that have specific outputs that feed the theme. The LEAG regards sustainability as the key to all of this, which means: don't abandon assets, leverage them; define commercial on ramps, and finally international cooperation is critical. Sustained lunar activity is only viable if it has an ongoing return of value. The more fields that are identified to have ongoing value generation, the more viable lunar operations become. Of these fields, the most important is the commercial one.

More about the LEAG Lunar Exploration Roadmap can be found on the LEAG website: https://www.lpi.usra.edu/leag/roadmap/index.shtml

4.5 Workshop guidelines and organization – George Sowers, Colorado School of Mines

The overall objective of the LPP workshop was to develop a roadmap to fill in the proposed mining strategic knowledge gaps—a resource exploration roadmap—to enable lunar mining operations in ten years.

Teams were organized into one of three phases of lunar ice exploration and prospecting: remote sensing, low cost impactors and landers, and rovers/samplers/analyzers. Each team was asked to submit up to four proposed missions for their section. Missions may be sequential or different approaches to the same problem. At the end of the workshop teams were asked to submit the following for each mission:

- Objectives
    - Data produced
    - SKG addressed
- Pre-Requisites
    - Missions
    - Data
    - Infrastructure
- Description
    - Instruments
    - Spacecraft
    - Estimated mass
    - Concept of Operations
- Required Technology development
- Timeframe
- Rough Order of Magnitude cost

5.0 Findings

There were 110 people registered for the workshop. Approximately 60 people participated for both days of the workshop (June 14-15, 2018). Nine teams developed mission strategies in three focus areas: remote sensing (2 teams), low cost landers and impactors (3 teams), rovers and samplers (4 teams). Each team prepared a presentation of their mission scenarios and presented it to the group during day two. The team presentations are included in Appendix B. Lively discussions occurred within the teams and in the large group setting. Key discussion points and findings follow.

Finding 1.

Use of the term prospecting should be avoided. The process to definitively characterize a space resource such that it becomes a proven reserve should be referred to as space resource exploration.

Prospecting has a connotation of a somewhat random process involving, perhaps, miners with picks and mules. Modern oil and gas and mineral exploration is a systematic process that results in the definitive characterization of a resource as a proven reserve. If the space resources community is to gain credibility with the terrestrial extractive industries, use of their terminology and methods (so far as practical) should be encouraged. It is recognized that the term exploration within the space community has typically referred to human exploration of space or scientifically driven missions. Hence there has been the tendency to prefer the term prospecting in space circles for identifying resources for utilization purposes.

Finding 2.

Mining strategic knowledge gaps (SKGs) provide a useful guide in developing a space resource exploration campaign.

The strategic knowledge gap (SKG) is a concept employed by the Human Exploration and Operations Mission Directorate (HEOMD) to define areas of scientific or practical ignorance that should be targeted by future missions, instruments or investigations. At the request of HEOMD, a LEAG Specific Action Team compiled the most recent set of SKGs in 2016 to reflect the enormous progress made by the LRO and LCROSS missions since the original lunar SKGs were formulated. The lunar SKGs can be found here (https://www.nasa.gov/sites/default/files/atoms/files/leag-gap-review-sat-2016-v2.pdf) and cover three themes.

I. Understand the lunar resource potential
II. Understand the lunar environment and its effect on human life
III. Understand how to work and live on the lunar surface

Of these, Theme I is clearly relevant to the question of lunar resource exploration. In particular, Theme I Category D, Polar Resources, addresses some of the issues associated with lunar polar ice exploration.

However, the existing LEAG SKG's were focused on NASA's needs as relevant to the Global Exploration Roadmap, and thus do not include the specific information needed to characterize lunar ice as a proven reserve for commercial or economic purposes. To make progress in this direction, specific mining SKGs were developed informed by a mining architecture created at the Colorado School of Mines in 2017 (Dreyer et. al., 2018) and a corresponding business case analysis (Sowers, 2018). Three mining SKGs were developed and presented in the introduction of the workshop (see section 4.2 above):

1. **The location of economically viable ice deposits in the lunar polar regions**
    - Economic viability is defined based on the mining architecture and business case developed by CSM
    - ≥25,000 mT total extractable ice; ≥4% ice by weight; ≥54kg/m^3 in first m; ≥1km^2 area
2. **The physical characteristics of the icy regolith within the PSRs**
    - Bulk & ice density, thermal properties, mechanical properties, variations with depth, presence and characteristics of other volatiles, etc.
3. **Characterization of ice deposit sites (operational considerations)**
    - Proximity to sunlight, surface properties, environments

The proposed mining SKGs provided the basis for the teams to propose mission scenarios as the resource exploration campaign, to be successful, must close each gap completely.

Finding 3.

The combination of the LRO and other lunar orbiting spacecraft have provided a solid foundation of remote sensing data of the lunar poles. But the resolution of the data is insufficient to meet the mining SKGs (10-20 km resolution for neutron data [H detection] versus <100 m required). However, proper interpretation of existing and future remote sensing data requires ground truth; i.e. direct confirmation of surface and subsurface conditions corresponding to a particular remote sensing signature.

Terrestrial resource exploration is aided by an in-depth understanding of the geologic processes and structures associated with particular types of resources. For example, oil deposits occur in particular sedimentary rock formations with specific features grounded by well substantiated geologic theory. This foundation informs and guides the exploration campaign, dramatically enhancing the effectiveness and efficiency of the exploration process.

Unfortunately, our understanding of lunar resource geology is far less mature, especially with regards to the processes that gave rise to large concentrations of water ice and other volatiles at the lunar poles. Without that underlying knowledge and a corresponding theoretical framework, the existing remote sensing data is subject to widely varying interpretations. For example, some believe the existing data is consistent with ice in the form of dirty snow on the surface. Others believe the icy regolith is hard and dense.

Hence, even though higher fidelity remote sensing data will ultimately be needed to characterize lunar ice as a proven reserve, a higher priority is obtaining some definitive ground truth in a few key locations near the poles.

Finding 4.

The use of large numbers of mass-produced, low-cost exploration devices will greatly enhance the cost effectiveness of the lunar resource exploration campaign.

Lunar resource characterization to the point of identifying a proven reserve requires data of very high spatial resolution. Many geographic locales need to be mapped in detail. The required data constitutes a relatively limited instrument set at relatively low precision compared to typical science missions. Use of complex machines like NASA's Mars rovers is likely cost prohibitive. Lessons from the ongoing cubesat revolution should be applied to developing mass-produced, low-cost exploration machines. Cubesat swarms for remote sensing, impactor swarms, wire guided ejectable sensor packages from a stationary lander and cubesat rover swarms can all play a major role while minimizing cost.

Finding 5.

Resource exploration must be viewed as an orchestrated campaign, not a set of independent missions. Each mission in the campaign builds off the ones before and provides a foundation for the ones that come later. However, given financial and time constraints, there is great value in rapid and parallel operations in mission development and execution.

The objective of lunar resource exploration is the economic development of the resources. The longer the exploration takes and the more it costs, the lower the economic return. It is therefore important to minimize both the cost and timeline of the exploration campaign. Proven business methods like agile development should be employed to minimize cost and schedule.

Finding 6.

Any use of high cost, complex rovers should be minimized and employed only as a final verification in a location where there is high confidence an economically viable resource exists.

It might be the case that a proven reserve cannot be defined without data from a more complex rover. This rover would be capable of obtaining subsurface information from multiple locations through the use of a sophisticated drilling/sensing apparatus. It would also be able to analyze samples of material from both surface and subsurface locations for chemical composition and geotechnical properties.

If such a rover mission is required, it would be economically harmful if the location did not harbor an economically viable resource. In the oil and gas industry, such a situation is called a "dry hole." Dry holes result in a large investment being expended with zero return and can bankrupt a company or end a program.

Any complex mission should be to a location where there is high confidence that the resource exists. The purpose of the mission would be to obtain a precise mapping of the deposit so the economic value can be established. In addition, including a demonstration of the ice extraction technology should be considered.

6.0 Recommendations

Based on the findings and the mission scenarios suggested by the nine workshop teams, the following recommendations can be made:

Recommendation 1.

The first priority for the lunar ice exploration campaign is to obtain ground truth in one or two key locations. This can be obtained by a lander equipped with a drill and other instruments to detect volatile species. Data from this mission will be used to anchor geologic models of the nature and formation of the lunar poles and their ice deposits. The data will also be used to calibrate existing remote sensing data for use in site selection for follow-on missions.

Recommendation 2.

Geologic models and resource maps should be developed, then refined throughout the exploration campaign.

Recommendation 3.

In parallel with the ground truth landers, a cubesat swarm should be employed to gather high resolution remote sensing data at the lunar poles relevant to the existence and characterization of water. The cubesats should fly as low as possible (10-20 km above the surface). The same mission should also deploy a swarm of hundreds of low cost impactors instrumented for volatile detection and quantification.

Recommendations 1-3 constitute phase I of the exploration campaign.

Recommendation 4.

Based on the previous results, a small number of the most promising locations should be selected. For each location, a small lander will be deployed. Each lander is equipped with a number of deployable, tethered sensor packages.

Recommendation 4 constitutes phase II of the exploration campaign.

Recommendation 5.

Based on the previous results, and if a sufficiently high probability location(s) has been found, a rover/sampler mission should be sent to that location for detailed resource mapping and verification of economic viability. This mission should include an ice extraction technology demonstration. Power options for this mission, which will require long duration operations within the PSR, include an RTG and a separate power beaming lander in an adjacent sunlit region with view into the PSR.

Recommendation 5 constitutes phase III of the exploration campaign. At the end of this phase sufficient information should be available to make rational investment decisions regarding the emplacement of the mining operation.

These recommendations represent four to eight missions depending on the number of sites investigated in addition to a corresponding modeling and mapping activity. To the extent possible, the missions should make use of common hardware and instruments. Some of the missions would make excellent candidates for payloads on NASAs new Commercial Lunar Payload Services (CLPS) program. Many architectural details remain to be worked out. For example, many different kinds of instruments were discussed at the workshop, any of which may be appropriate for these missions. Remote sensing instruments include optical, hyperspectral, infra-red, neutron and gamma ray spectrometers, and more. Instruments for landed missions include all those for remote sensing in addition to ground penetrating radar, seismic, as well as a myriad of geotechnical and chemical analysis instruments. Many systems engineering trade studies, analyses and prototypes should be conducted/developed to fine tune this campaign framework.

Recommendation 6.

NASA should direct the LEAG to convene a Specific Action Team (SAT) to develop the details of the lunar polar ice exploration roadmap sufficient to begin mission planning.

The four mission categories contained in the recommendations are summarized in Table 2. Figure 8 lays the campaign out on a timeline starting now and leading to industrial production of LO_2/LH_2 propellants within the decade. The total cost of the exploration campaign should be kept under $1B.

Table 2. *Recommended lunar polar ice exploration missions.*

Mission Description	Number	Timeframe (launch)	ROM Cost	Objectives/SKGs addressed
Ground truth lander(s)	1-2	2021	$100M ea	Anchor geologic models, calibrate remote sensing data
Cubesat swarm, impactor swarm	1	2021	$100M	High resolution remote sensing data; large number of ground truth data points/Location of ice deposits
Tethered sensor landers	1-5	2023	$100M ea	Richness of ice deposits, characterization of ice deposits, characterization of site.
Rover/sampler	1-2	2025	$200M ea	Verification of economic viability, mapping of the deposit, extraction demo

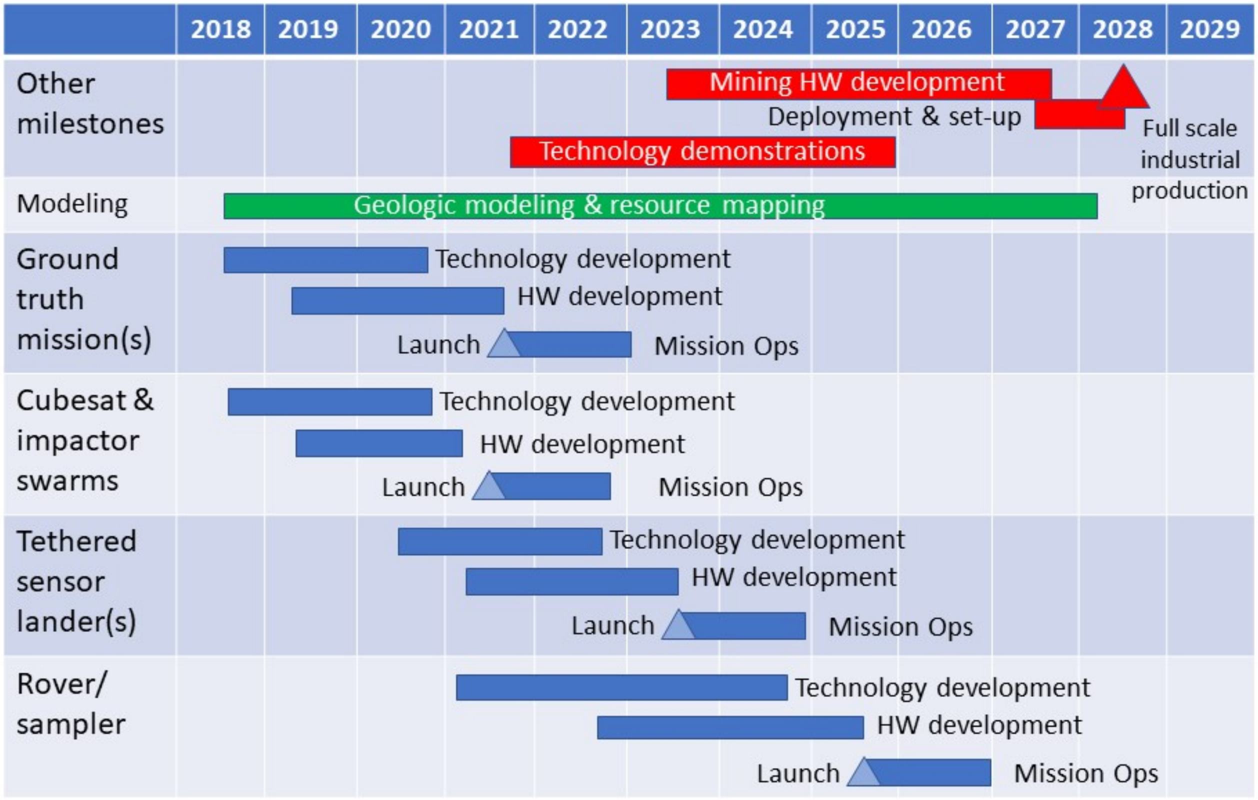


Figure 8. *Roadmap for lunar polar ice resource exploration campaign.*

7.0 References

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8.0 Appendix A:

All of the presentations introducing the workshop are available online on the Space Resources roundtable website: http://isruinfo.com/index.php?page=srr_19_ptmss Specific links to each presentation are provided below.

8.1 Workshop Introduction – George Sowers, Colorado School of Mines

http://isruinfo.com/docs/srr19_ptmss/W1-Introduction-Sowers.zip

8.2 State of Knowledge of Lunar Polar Ice and Volatiles – Clive R. Neal, University of Notre Dame

http://isruinfo.com/docs/srr19_ptmss/W2-State%20of%20Knowledge%20of%20Lunar%20Polar%20Ice%20and%20Volatiles-Neal.zip

8.3 Lunar Ice Mining Strategic Knowledge Gaps – George Sowers, Colorado School of Mines

http://isruinfo.com/docs/srr19_ptmss/W4-Lunar%20Ice%20Mining%20SKGs-Sowers.zip

8.4 Summary of Prospecting Technologies – Chris Dreyer, Colorado School of Mines

http://isruinfo.com/docs/srr19_ptmss/W5-Summary%20of%20Prospecting%20Technologies-Dreyer.zip

8.5 LEAG Lunar Exploration Roadmap – Clive R. Neal, University of Notre Dame

http://isruinfo.com/docs/srr19_ptmss/W3-LEAG%20Lunar%20Exploration%20Roadmap-Neal.zip

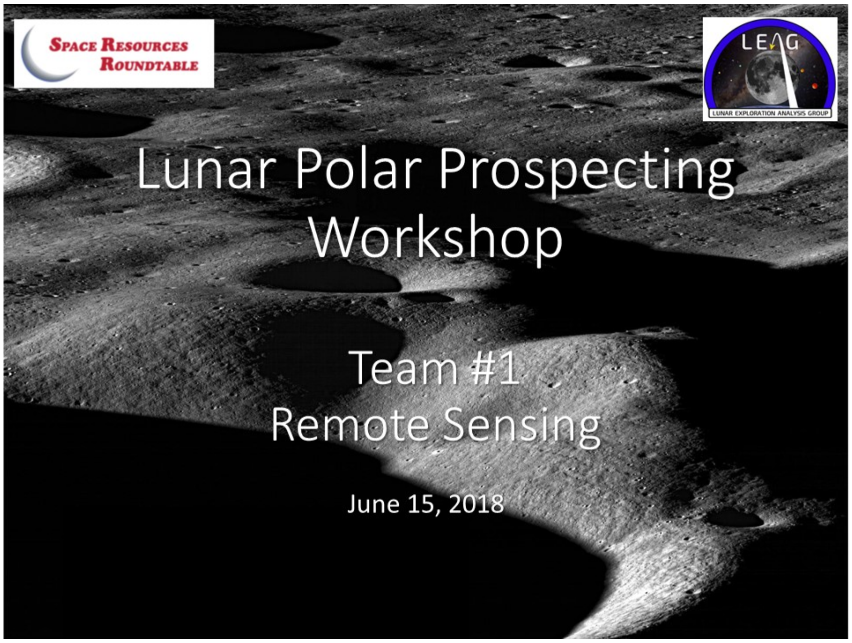
8.6 Workshop guidelines and organization – George Sowers, Colorado School of Mines

http://isruinfo.com/docs/srr19_ptmss/W6-Team%20Introduction.zip

Appendix B:

Each team prepared a presentation of their mission scenarios. Those presentations are not available online but are reproduced below. Note that team 3 was absorbed into other teams due to insufficient membership and does not have a presentation.

Team 1

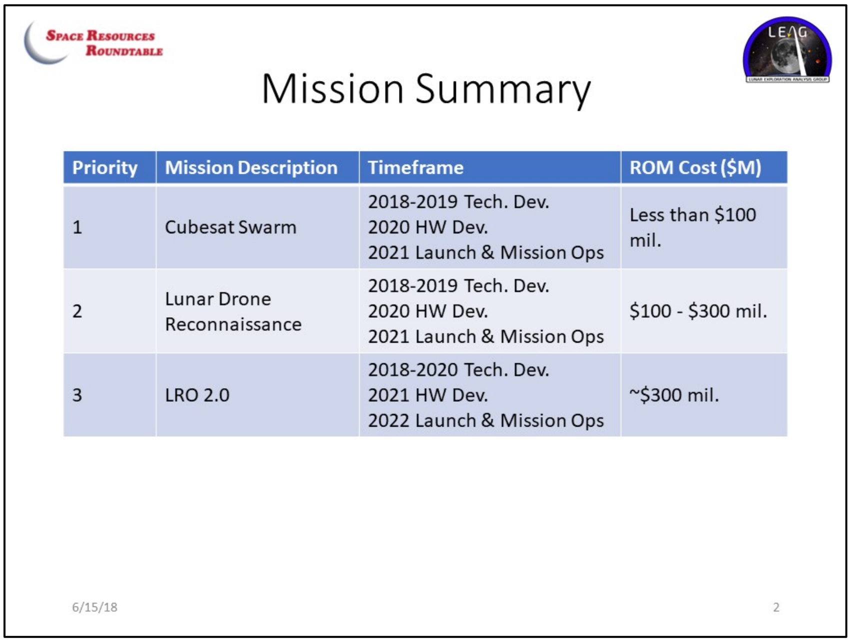


Space Resources
Roundtable

Lunar Polar Prospecting Workshop

Team #1
Remote Sensing

June 15, 2018

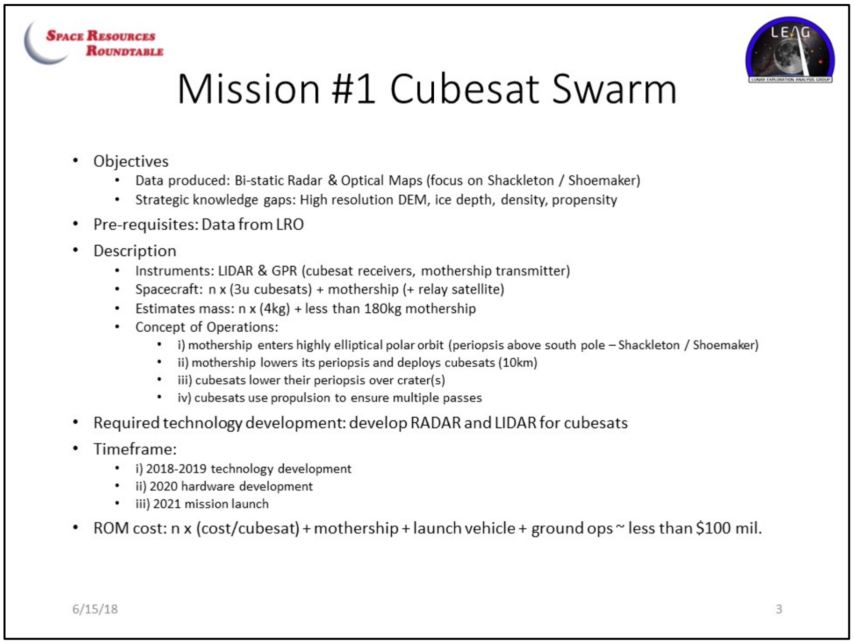


Space Resources
Roundtable

Mission Summary

Priority	Mission Description	Timeframe	ROM Cost ($M)
1	Cubesat Swarm	2018-2019 Tech. Dev. 2020 HW Dev. 2021 Launch & Mission Ops	Less than $100 mil.
2	Lunar Drone Reconnaissance	2018-2019 Tech. Dev. 2020 HW Dev. 2021 Launch & Mission Ops	$100 - $300 mil.
3	LRO 2.0	2018-2020 Tech. Dev. 2021 HW Dev. 2022 Launch & Mission Ops	~$300 mil.

6/15/18 2

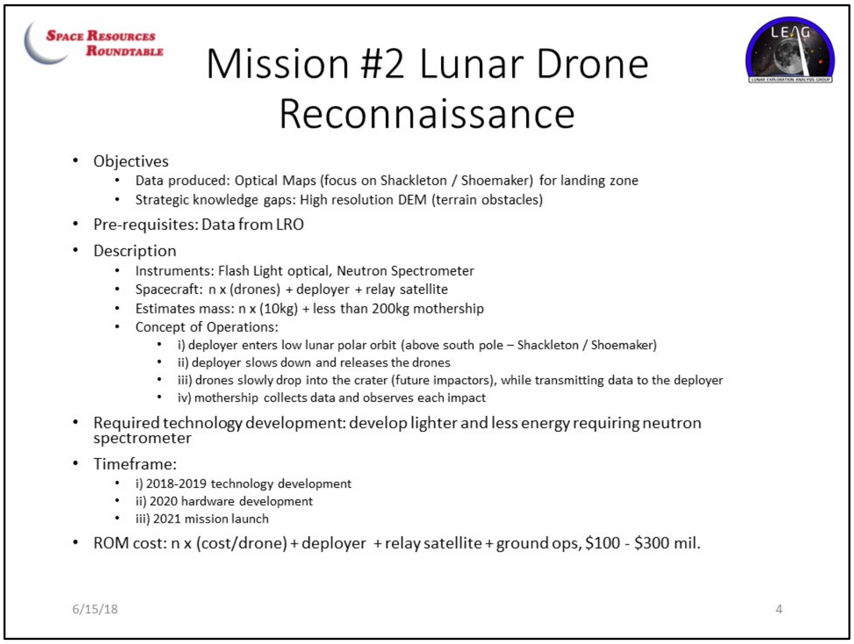


SPACE RESOURCES
ROUNDTABLE

Mission #1 Cubesat Swarm

- Objectives
  - Data produced: Bi-static Radar & Optical Maps (focus on Shackleton / Shoemaker)
  - Strategic knowledge gaps: High resolution DEM, ice depth, density, propensity
- Pre-requisites: Data from LRO
- Description
  - Instruments: LIDAR & GPR (cubesat receivers, mothership transmitter)
  - Spacecraft: n x (3u cubesats) + mothership (+ relay satellite)
  - Estimates mass: n x (4kg) + less than 180kg mothership
  - Concept of Operations:
    - i) mothership enters highly elliptical polar orbit (periopsis above south pole – Shackleton / Shoemaker)
    - ii) mothership lowers its periopsis and deploys cubesats (10km)
    - iii) cubesats lower their periopsis over crater(s)
    - iv) cubesats use propulsion to ensure multiple passes
- Required technology development: develop RADAR and LIDAR for cubesats
- Timeframe:
  - i) 2018-2019 technology development
  - ii) 2020 hardware development
  - iii) 2021 mission launch
- ROM cost: n x (cost/cubesat) + mothership + launch vehicle + ground ops ~ less than $100 mil.

6/15/18 3

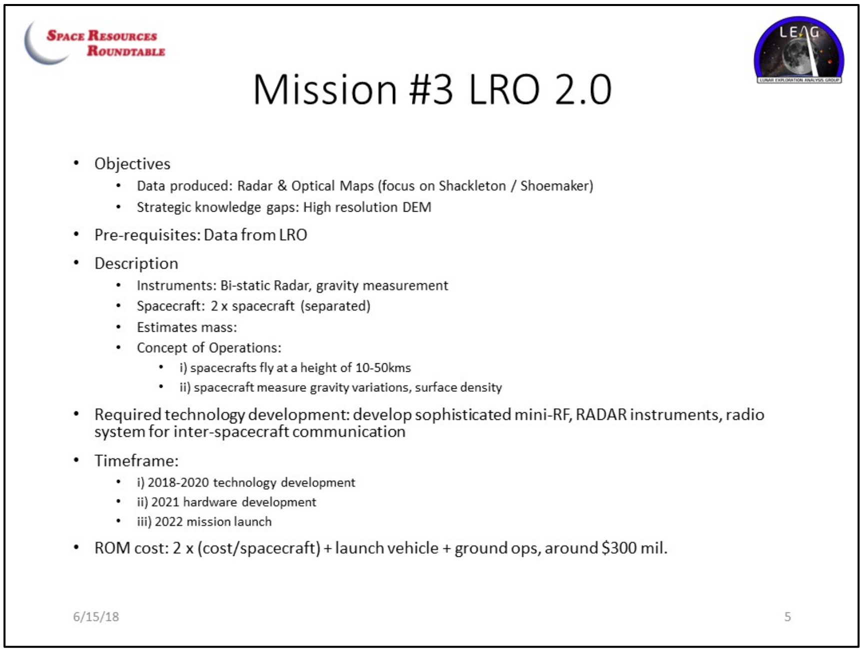


SPACE RESOURCES
ROUNDTABLE

Mission #2 Lunar Drone Reconnaissance

- Objectives
  - Data produced: Optical Maps (focus on Shackleton / Shoemaker) for landing zone
  - Strategic knowledge gaps: High resolution DEM (terrain obstacles)
- Pre-requisites: Data from LRO
- Description
  - Instruments: Flash Light optical, Neutron Spectrometer
  - Spacecraft: n x (drones) + deployer + relay satellite
  - Estimates mass: n x (10kg) + less than 200kg mothership
  - Concept of Operations:
    - i) deployer enters low lunar polar orbit (above south pole – Shackleton / Shoemaker)
    - ii) deployer slows down and releases the drones
    - iii) drones slowly drop into the crater (future impactors), while transmitting data to the deployer
    - iv) mothership collects data and observes each impact
- Required technology development: develop lighter and less energy requiring neutron spectrometer
- Timeframe:
  - i) 2018-2019 technology development
  - ii) 2020 hardware development
  - iii) 2021 mission launch
- ROM cost: n x (cost/drone) + deployer + relay satellite + ground ops, $100 - $300 mil.

6/15/18 4

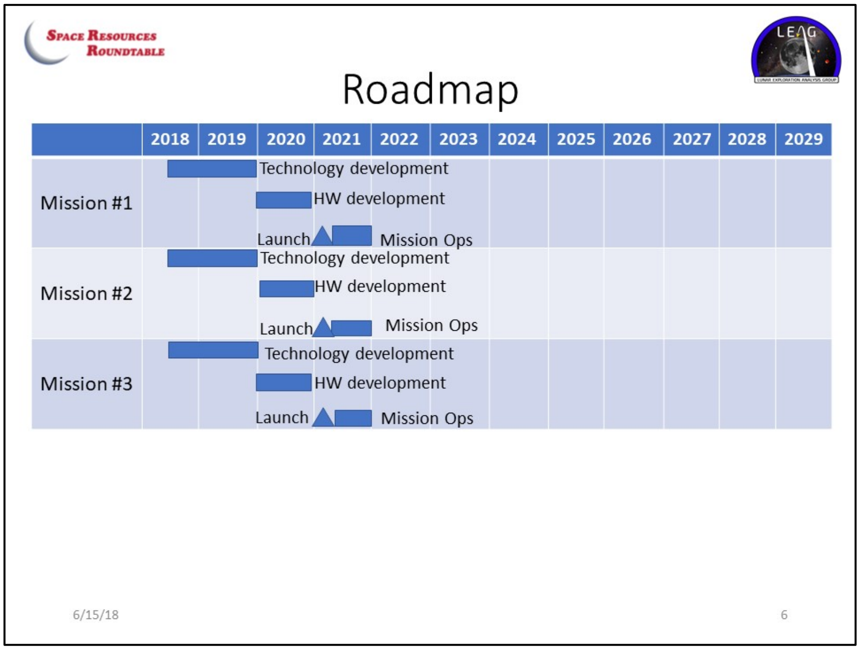


Space Resources Roundtable

Mission #3 LRO 2.0

- Objectives
  - Data produced: Radar & Optical Maps (focus on Shackleton / Shoemaker)
  - Strategic knowledge gaps: High resolution DEM
- Pre-requisites: Data from LRO
- Description
  - Instruments: Bi-static Radar, gravity measurement
  - Spacecraft: 2 x spacecraft (separated)
  - Estimates mass:
  - Concept of Operations:
    - i) spacecrafts fly at a height of 10-50kms
    - ii) spacecraft measure gravity variations, surface density
- Required technology development: develop sophisticated mini-RF, RADAR instruments, radio system for inter-spacecraft communication
- Timeframe:
  - i) 2018-2020 technology development
  - ii) 2021 hardware development
  - iii) 2022 mission launch
- ROM cost: 2 x (cost/spacecraft) + launch vehicle + ground ops, around $300 mil.

6/15/18 5

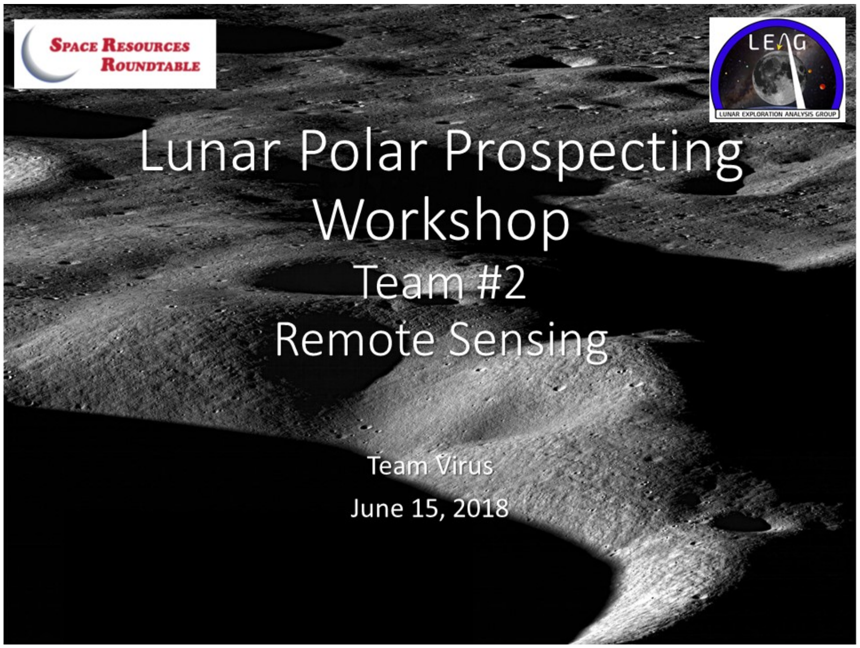


Space Resources Roundtable

Roadmap

6/15/18 6

Team 2



SPACE RESOURCES ROUNDTABLE

LEAG
LUNAR EXPLORATION ANALYSIS GROUP

Lunar Polar Prospecting Workshop
Team #2
Remote Sensing

Team Virus

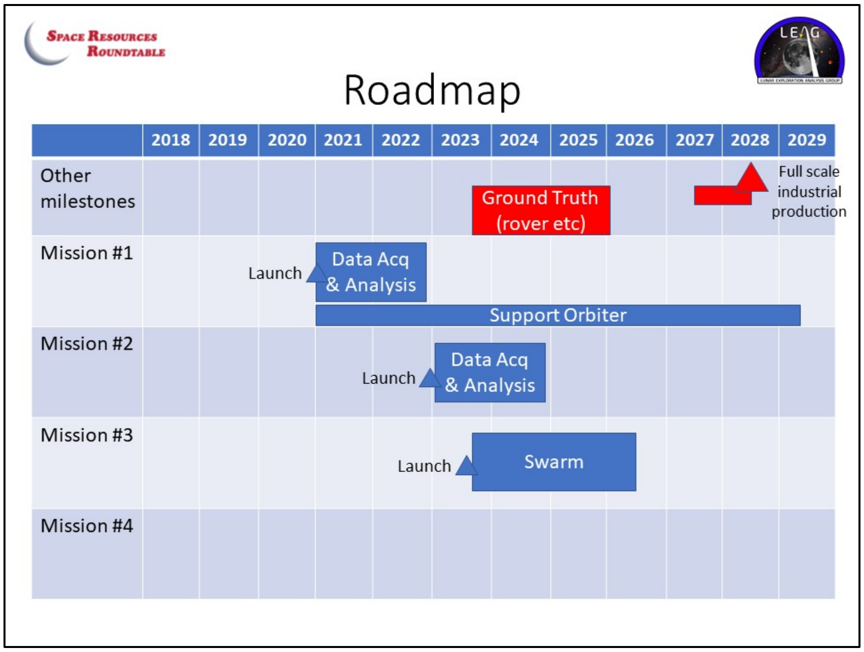
June 15, 2018

SPACE RESOURCES ROUNDTABLE

LEAG
LUNAR EXPLORATION ANALYSIS GROUP

Recommended Missions

Priority	Mission Description	Timeframe	ROM Cost ($M)
1	1 permanent multispec/GRS installation on 3 crater rims; full surface coverage of basin + orbiter multi/NS/GRS	2021- … 2021 - 2022	$250M (orbiter) $200M (installs)
2	2 additional installations on top crater (multispec/GRS);	2023-2025	$150M
3	Lander with swarm (10) of mobility platforms (IR)	2023-2026	$100M
4			



Roadmap

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Other milestones							Ground Truth (rover etc)				Full scale industrial production	
Mission #1			Launch	Data Acq & Analysis Support Orbiter								
Mission #2					Launch	Data Acq & Analysis						
Mission #3						Launch	Swarm					
Mission #4												

Mission #1 Detail

- Objectives
  - IR gives water ice, GRS gives H, high resolution
  - Strategic knowledge gaps addressed
- Pre-requisites
  - What missions/data/infrastructure needs to enable and/or inform this mission
- Description
  - Instruments
  - Spacecraft
  - Estimates mass
  - Concept of Operations
- Required technology development
- Timeframe
- ROM cost

Mission #2 Detail

- Objectives
  - Data produced
  - Strategic knowledge gaps addressed
- Pre-requisites
  - What missions/data/infrastructure needs to enable and/or inform this mission
- Description
  - Instruments
  - Spacecraft
  - Estimates mass
  - Concept of Operations
- Required technology development
- Timeframe
- ROM cost

Mission #3 Detail

- Objectives
  - Data produced
  - Strategic knowledge gaps addressed
- Pre-requisites
  - What missions/data/infrastructure needs to enable and/or inform this mission
- Description
  - Instruments
  - Spacecraft
  - Estimates mass
  - Concept of Operations
- Required technology development
- Timeframe
- ROM cost

Mission #4 Detail

- Objectives
  - Data produced
  - Strategic knowledge gaps addressed
- Pre-requisites
  - What missions/data/infrastructure needs to enable and/or inform this mission
- Description
  - Instruments
  - Spacecraft
  - Estimates mass
  - Concept of Operations
- Required technology development
- Timeframe
- ROM cost

Team 4

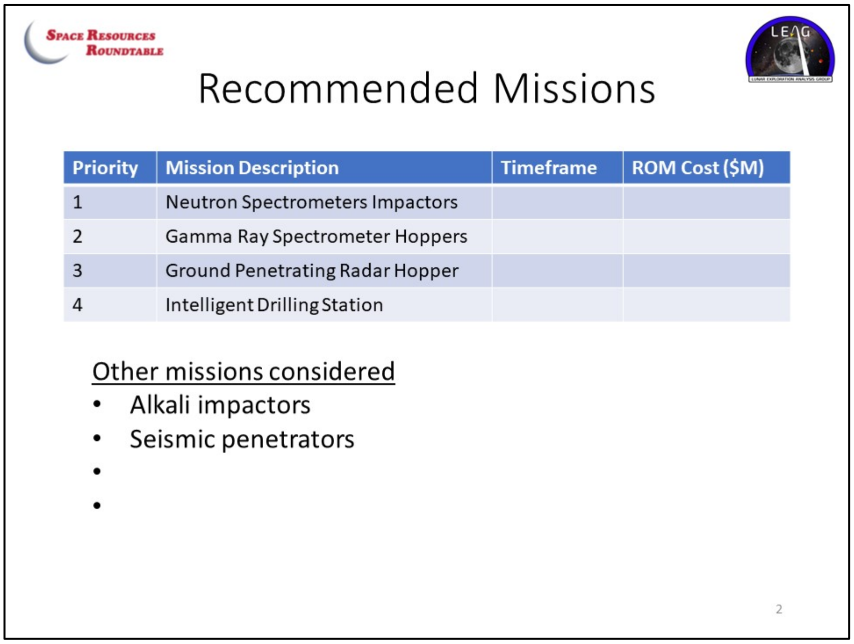
Lunar Polar Prospecting Workshop

Team #4

Landers/Impactors

Team Templates

June 15, 2018



Recommended Missions

Priority	Mission Description	Timeframe	ROM Cost ($M)
1	Neutron Spectrometers Impactors		
2	Gamma Ray Spectrometer Hoppers		
3	Ground Penetrating Radar Hopper		
4	Intelligent Drilling Station		

Other missions considered

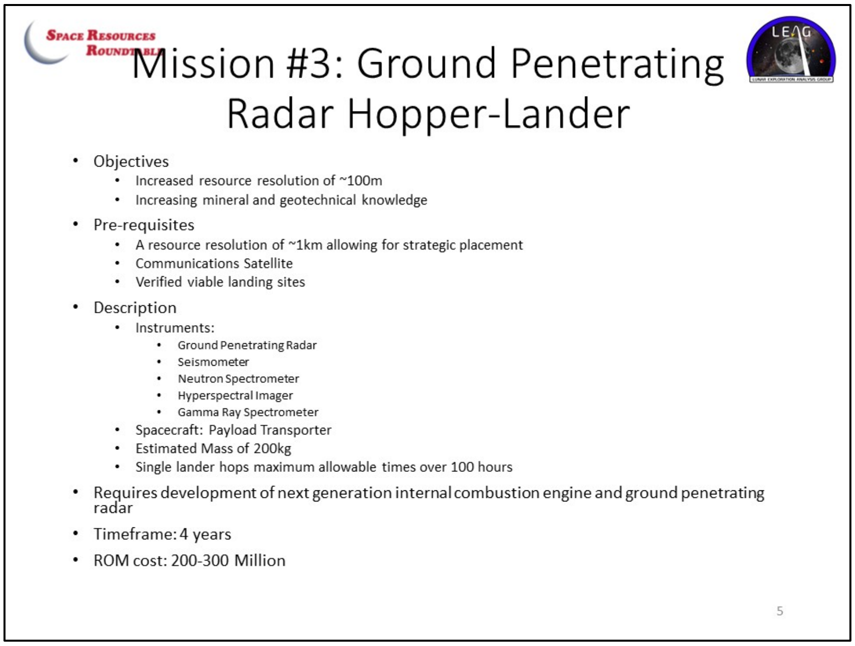
- Alkali impactors
- Seismic penetrators

Mission #1: Neutron Spectrometer Impactors

- Objectives
  - Coarse resolution of crater floor composition
  - Provides a roadmap for closer inspection with a resolution <10km
- Pre-requisites
  - Orbital data providing a resolution of 10km
  - Communications satellite
  - Ground communicator
- Description
  - Instruments: Neutron Spectrometers
  - Spacecraft: Payload Transporter
  - Estimated Sum Mass of 50kg
  - Multiple one shot impactor payloads provide large area surveys over the course of 16hours
- Requires the development of small scale, mass produced neutron spectrometers.
- Timeframe: 3 years
- ROM Cost: 50 million NRE, 50 million per mission

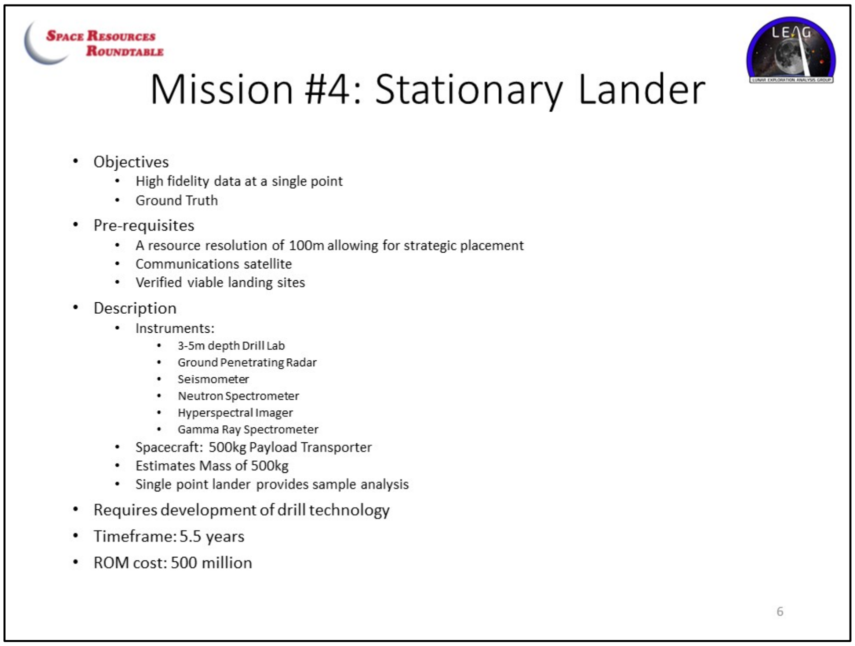
Mission #2: Gamma Ray Spectrometer Hoppers

- Objectives
  - Measures surface composition to a resolution of 1km
  - Provides higher spatial resolution of a promising locations
- Pre-requisites
  - A resource resolution of ~5km allowing for strategic placement
  - Communications satellite
  - Verified viable landing sites
  - Ground communicator
- Description
  - Instruments:
    - Gamma Ray Spectrometers
    - Seismometers
    - Neutron Spectrometers
    - Dust Characterizers
  - Spacecraft: Payload Transporter
  - Estimated Sum Mass of 400kg
  - Hoppers deploy from landers, collect data over the course of three hops over the course of 32 hours
- Requires development of reliable hopper technology
- Timeframe: 3.5 years
- ROM Cost: 200-300 million



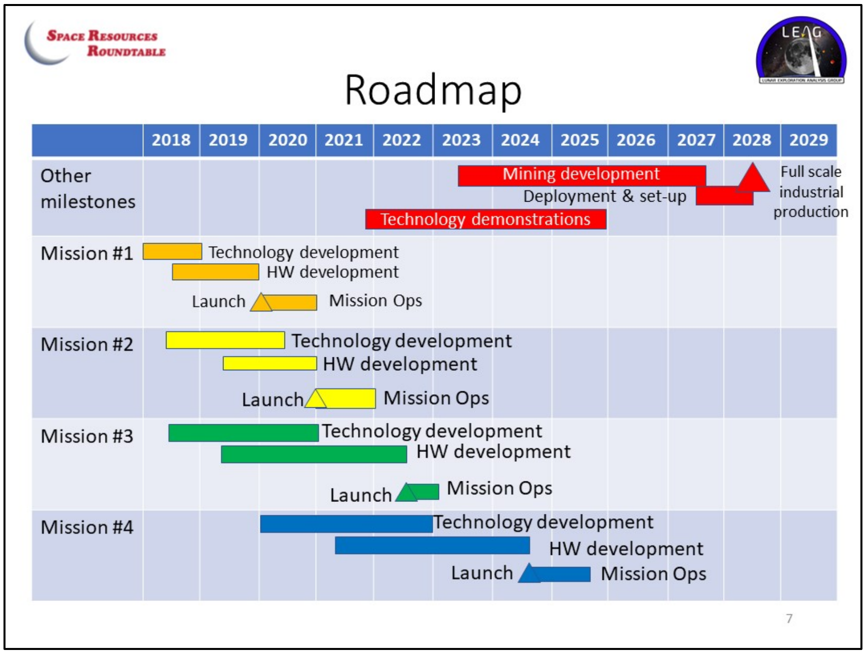
Mission #3: Ground Penetrating Radar Hopper-Lander

- Objectives
  - Increased resource resolution of ~100m
  - Increasing mineral and geotechnical knowledge
- Pre-requisites
  - A resource resolution of ~1km allowing for strategic placement
  - Communications Satellite
  - Verified viable landing sites
- Description
  - Instruments:
    - Ground Penetrating Radar
    - Seismometer
    - Neutron Spectrometer
    - Hyperspectral Imager
    - Gamma Ray Spectrometer
  - Spacecraft: Payload Transporter
  - Estimated Mass of 200kg
  - Single lander hops maximum allowable times over 100 hours
- Requires development of next generation internal combustion engine and ground penetrating radar
- Timeframe: 4 years
- ROM cost: 200-300 Million



Mission #4: Stationary Lander

- Objectives
  - High fidelity data at a single point
  - Ground Truth
- Pre-requisites
  - A resource resolution of 100m allowing for strategic placement
  - Communications satellite
  - Verified viable landing sites
- Description
  - Instruments:
    - 3-5m depth Drill Lab
    - Ground Penetrating Radar
    - Seismometer
    - Neutron Spectrometer
    - Hyperspectral Imager
    - Gamma Ray Spectrometer
  - Spacecraft: 500kg Payload Transporter
  - Estimates Mass of 500kg
  - Single point lander provides sample analysis
- Requires development of drill technology
- Timeframe: 5.5 years
- ROM cost: 500 million



Space Resources Roundtable

Roadmap

7

Team 5

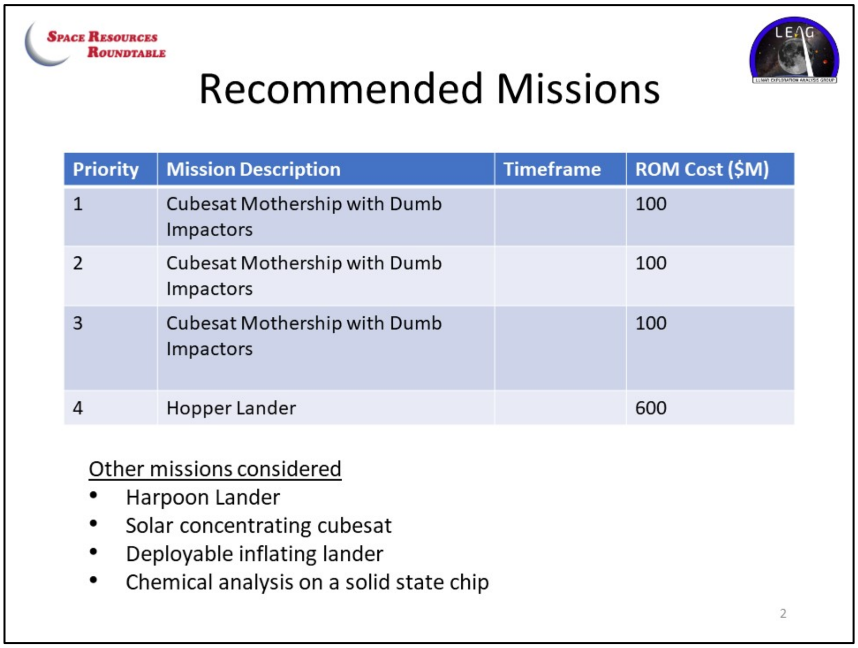
Lunar Polar Prospecting Workshop

Team #x

Category

Team Templates

June 15, 2018

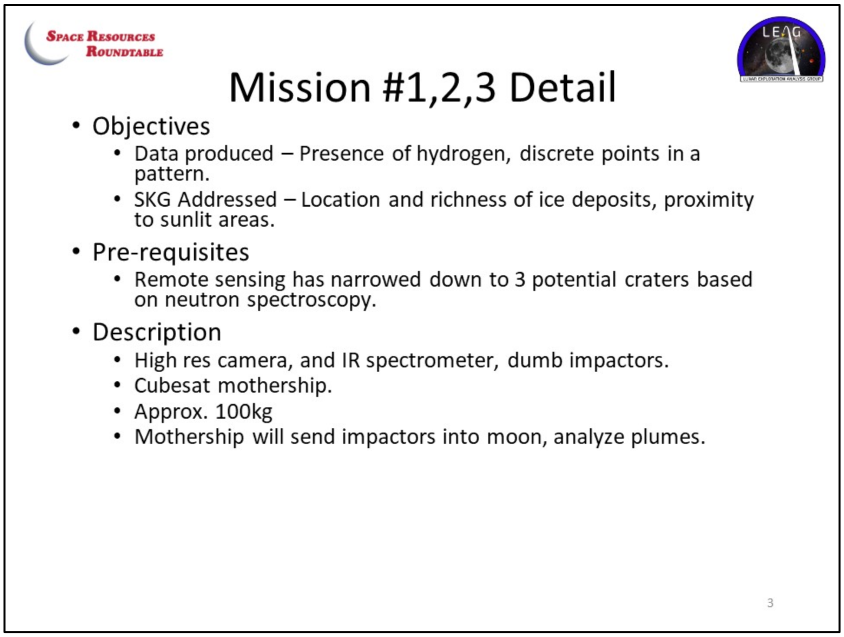


Recommended Missions

Priority	Mission Description	Timeframe	ROM Cost ($M)
1	Cubesat Mothership with Dumb Impactors		100
2	Cubesat Mothership with Dumb Impactors		100
3	Cubesat Mothership with Dumb Impactors		100
4	Hopper Lander		600

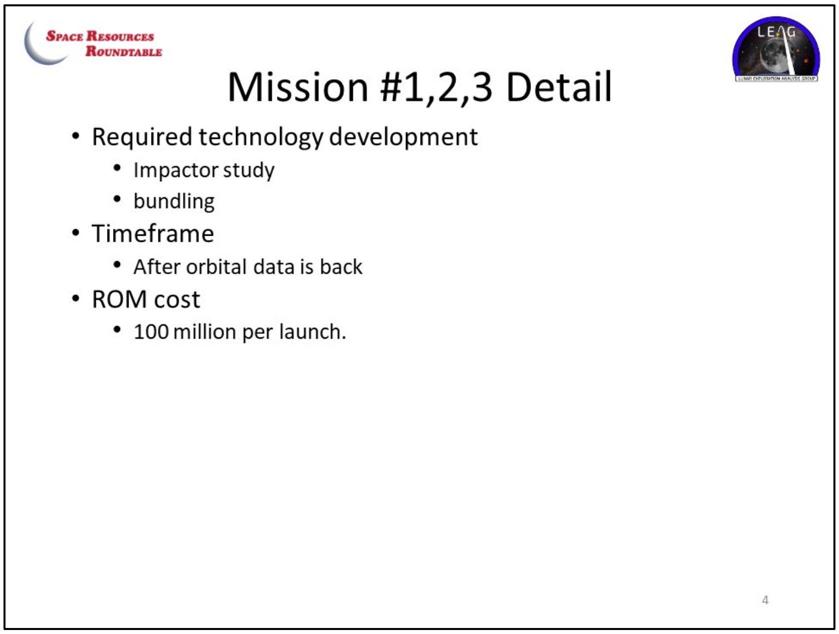
Other missions considered

- Harpoon Lander
- Solar concentrating cubesat
- Deployable inflating lander
- Chemical analysis on a solid state chip



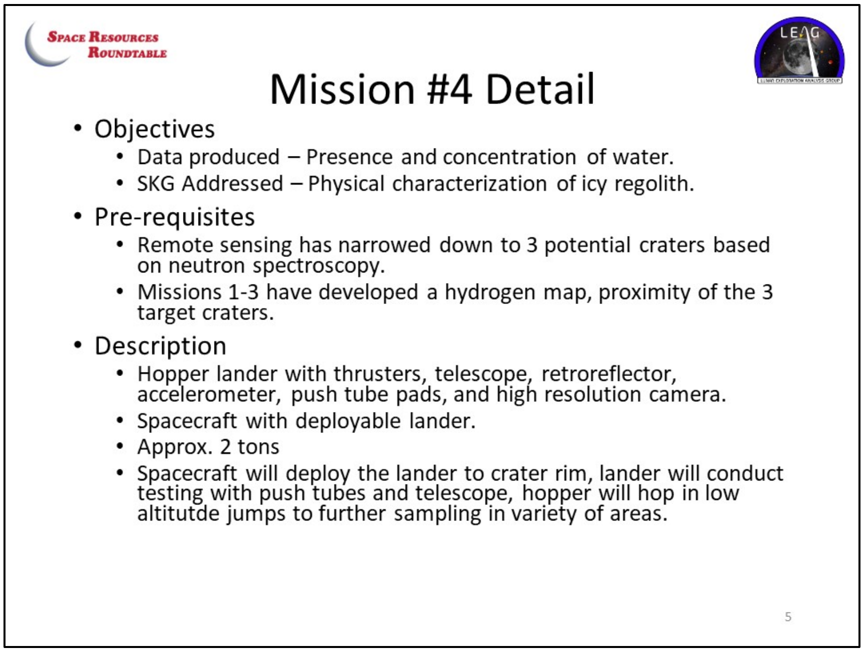
Mission #1,2,3 Detail

- Objectives
  - Data produced – Presence of hydrogen, discrete points in a pattern.
  - SKG Addressed – Location and richness of ice deposits, proximity to sunlit areas.
- Pre-requisites
  - Remote sensing has narrowed down to 3 potential craters based on neutron spectroscopy.
- Description
  - High res camera, and IR spectrometer, dumb impactors.
  - Cubesat mothership.
  - Approx. 100kg
  - Mothership will send impactors into moon, analyze plumes.



Mission #1,2,3 Detail

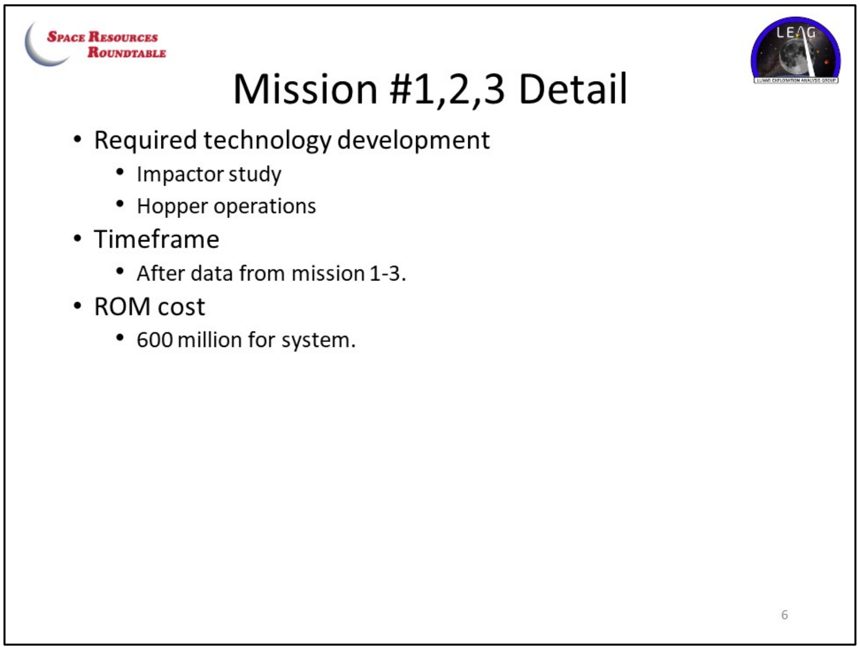
- Required technology development
  - Impactor study
  - bundling
- Timeframe
  - After orbital data is back
- ROM cost
  - 100 million per launch.



Space Resources Roundtable

Mission #4 Detail

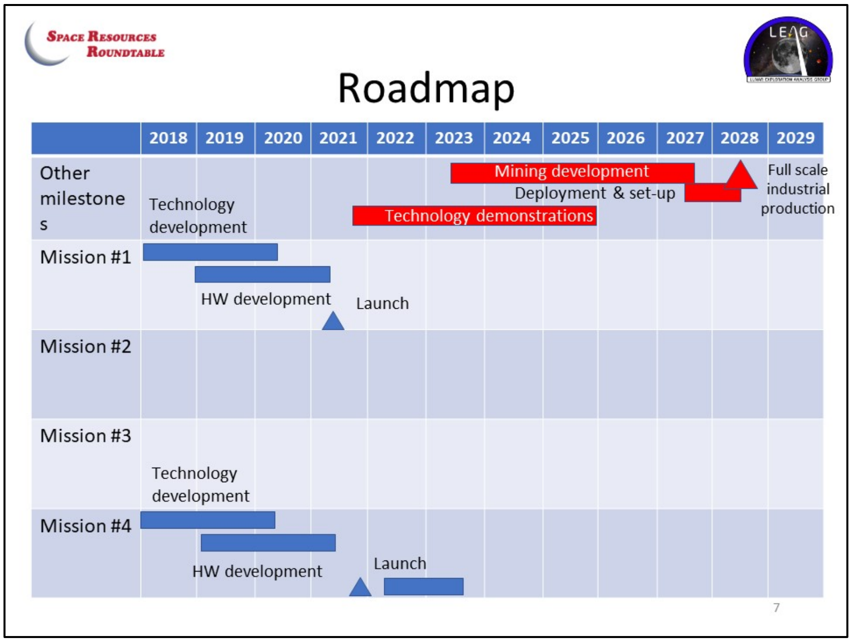
- Objectives
  - Data produced – Presence and concentration of water.
  - SKG Addressed – Physical characterization of icy regolith.
- Pre-requisites
  - Remote sensing has narrowed down to 3 potential craters based on neutron spectroscopy.
  - Missions 1-3 have developed a hydrogen map, proximity of the 3 target craters.
- Description
  - Hopper lander with thrusters, telescope, retroreflector, accelerometer, push tube pads, and high resolution camera.
  - Spacecraft with deployable lander.
  - Approx. 2 tons
  - Spacecraft will deploy the lander to crater rim, lander will conduct testing with push tubes and telescope, hopper will hop in low altitutde jumps to further sampling in variety of areas.



Space Resources Roundtable

Mission #1,2,3 Detail

- Required technology development
  - Impactor study
  - Hopper operations
- Timeframe
  - After data from mission 1-3.
- ROM cost
  - 600 million for system.



Space Resources Roundtable

Roadmap

7

Team 6

Space Resources Roundtable

LEAG Lunar Exploration Analysis Group

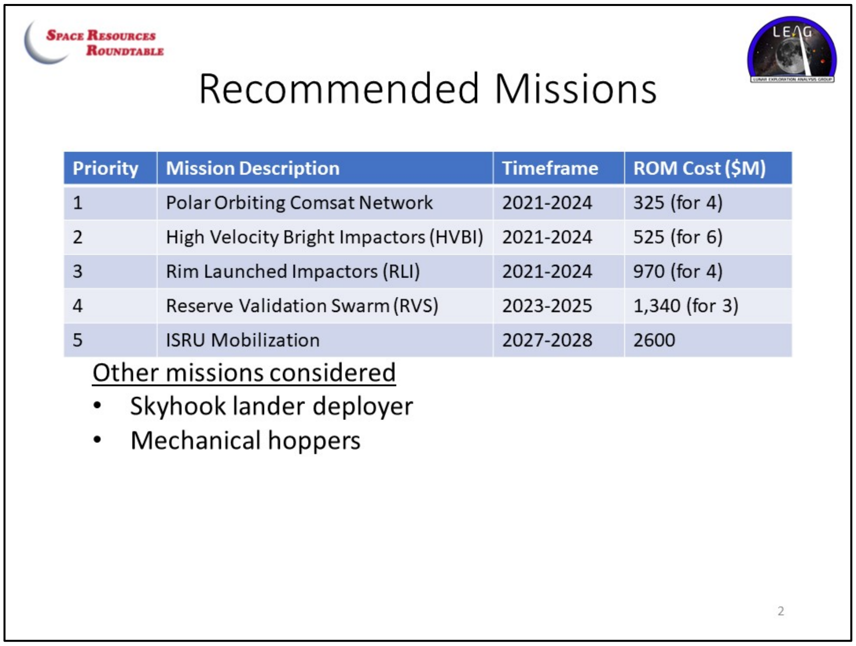
Lunar Polar Prospecting Workshop

Team 6

Impactors and Landers

Team Templates

June 15, 2018



Space Resources Roundtable

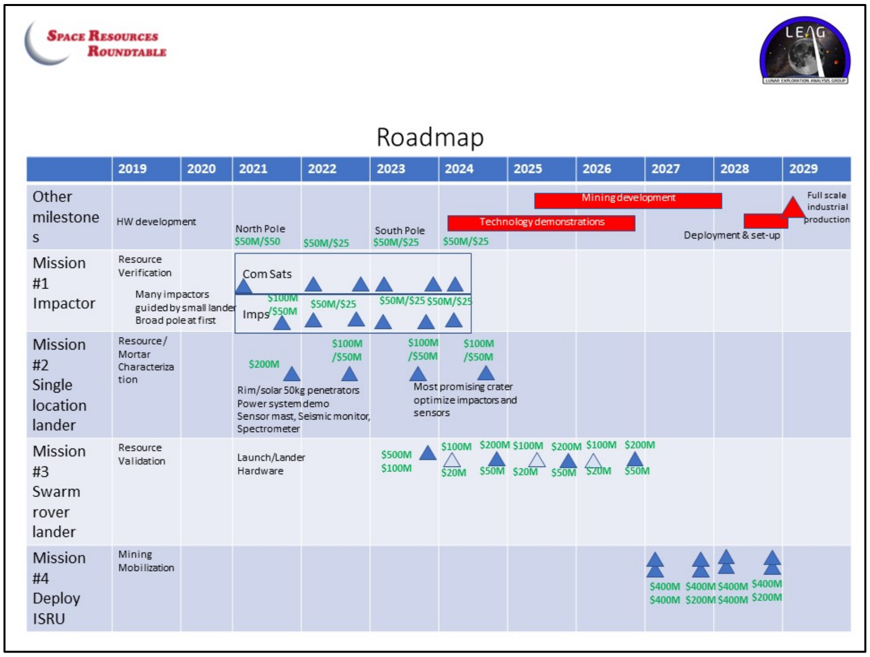
LEAG Lunar Exploration Analysis Group

Recommended Missions

Priority	Mission Description	Timeframe	ROM Cost ($M)
1	Polar Orbiting Comsat Network	2021-2024	325 (for 4)
2	High Velocity Bright Impactors (HVBI)	2021-2024	525 (for 6)
3	Rim Launched Impactors (RLI)	2021-2024	970 (for 4)
4	Reserve Validation Swarm (RVS)	2023-2025	1,340 (for 3)
5	ISRU Mobilization	2027-2028	2600

Other missions considered

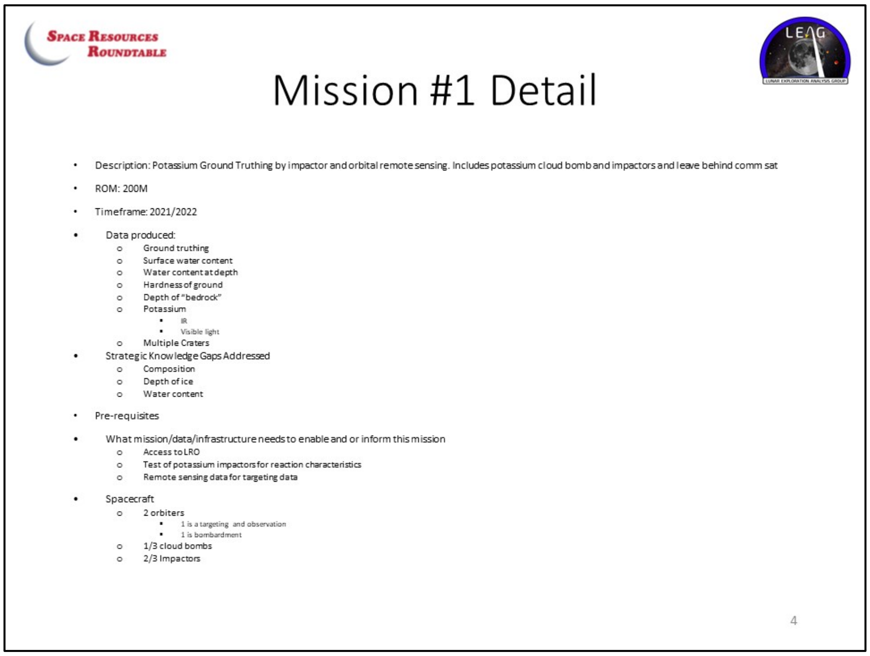
- Skyhook lander deployer
- Mechanical hoppers



Space Resources Roundtable

Roadmap

	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Other milestones	HW development		North Pole $50M/$50	$50M/$25	South Pole $50M/$25	Technology demonstrations $50M/$25	Mining development			Deployment & set-up	Full scale industrial production
Mission #1 Impactor	Resource Verification Many impactors guided by small lander Broad pole at first		Com Sats Imps $100M /$50M	$50M/$25	$50M/$25	$50M/$25					
Mission #2 Single location lander	Resource/ Mortar Characterization		$200M Rim/solar 50kg penetrators Power system demo Sensor mast, Seismic monitor, Spectrometer	$100M /$50M	$100M /$50M Most promising crater optimize impactors and sensors	$100M /$50M					
Mission #3 Swarm rover lander	Resource Validation		Launch/Lander Hardware		$500M $100M	$100M $20M $200M $50M	$100M $20M $200M $50M	$100M $20M $200M $50M			
Mission #4 Deploy ISRU	Mining Mobilization								$400M $400M $400M $200M	$400M $400M $400M $200M	

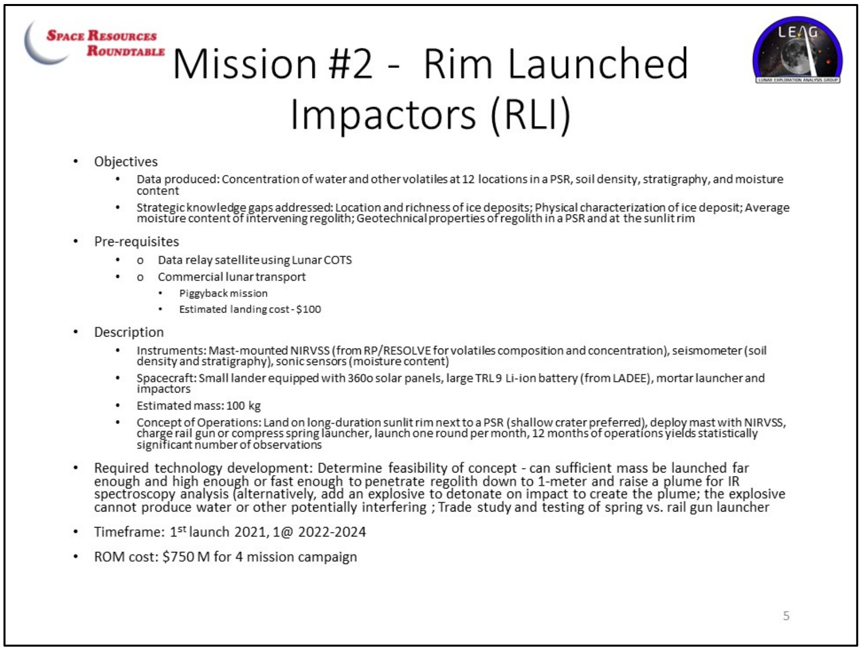


Space Resources Roundtable

Mission #1 Detail

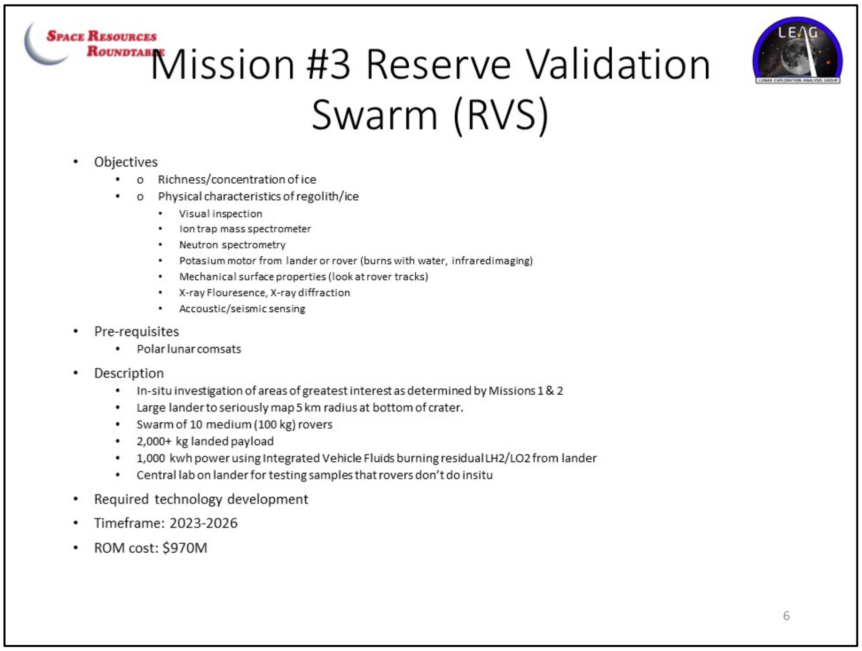
- Description: Potassium Ground Truthing by impactor and orbital remote sensing. Includes potassium cloud bomb and impactors and leave behind comm sat
- ROM: 200M
- Timeframe: 2021/2022
- Data produced:
  - Ground truthing
  - Surface water content
  - Water content at depth
  - Hardness of ground
  - Depth of "bedrock"
  - Potassium
    - IR
    - Visible light
  - Multiple Craters
- Strategic Knowledge Gaps Addressed
  - Composition
  - Depth of ice
  - Water content
- Pre-requisites
- What mission/data/infrastructure needs to enable and or inform this mission
  - Access to LRO
  - Test of potassium impactors for reaction characteristics
  - Remote sensing data for targeting data
- Spacecraft
  - 2 orbiters
    - 1 is a targeting and observation
    - 1 is bombardment
  - 1/3 cloud bombs
  - 2/3 Impactors

4



Mission #2 - Rim Launched Impactors (RLI)

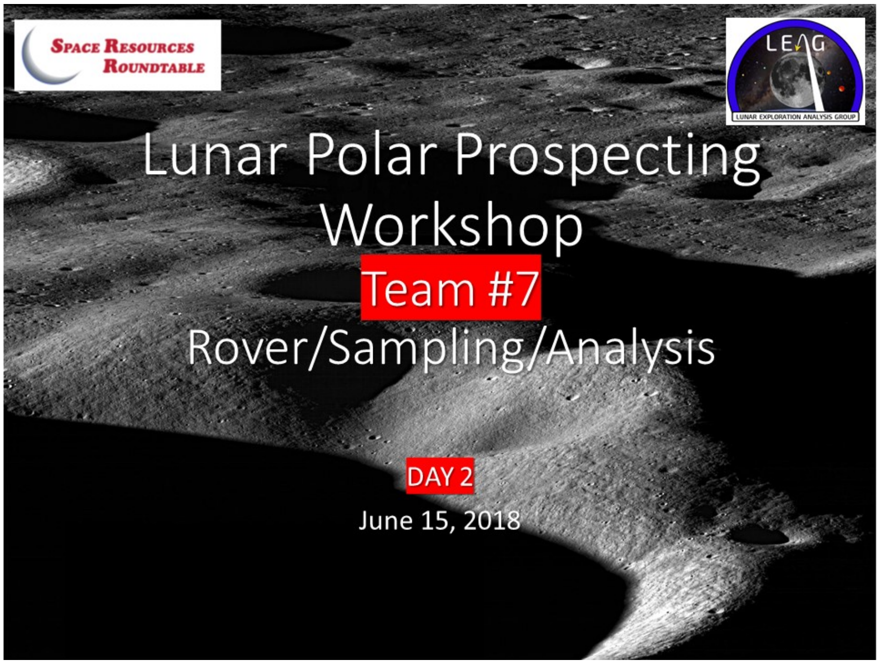
- Objectives
  - Data produced: Concentration of water and other volatiles at 12 locations in a PSR, soil density, stratigraphy, and moisture content
  - Strategic knowledge gaps addressed: Location and richness of ice deposits; Physical characterization of ice deposit; Average moisture content of intervening regolith; Geotechnical properties of regolith in a PSR and at the sunlit rim
- Pre-requisites
  - o Data relay satellite using Lunar COTS
  - o Commercial lunar transport
    - Piggyback mission
    - Estimated landing cost - $100
- Description
  - Instruments: Mast-mounted NIRVSS (from RP/RESOLVE for volatiles composition and concentration), seismometer (soil density and stratigraphy), sonic sensors (moisture content)
  - Spacecraft: Small lander equipped with 360o solar panels, large TRL 9 Li-ion battery (from LADEE), mortar launcher and impactors
  - Estimated mass: 100 kg
  - Concept of Operations: Land on long-duration sunlit rim next to a PSR (shallow crater preferred), deploy mast with NIRVSS, charge rail gun or compress spring launcher, launch one round per month, 12 months of operations yields statistically significant number of observations
- Required technology development: Determine feasibility of concept - can sufficient mass be launched far enough and high enough or fast enough to penetrate regolith down to 1-meter and raise a plume for IR spectroscopy analysis (alternatively, add an explosive to detonate on impact to create the plume; the explosive cannot produce water or other potentially interfering ; Trade study and testing of spring vs. rail gun launcher
- Timeframe: 1st launch 2021, 1@ 2022-2024
- ROM cost: $750 M for 4 mission campaign



Mission #3 Reserve Validation Swarm (RVS)

- Objectives
  - o Richness/concentration of ice
  - o Physical characteristics of regolith/ice
    - Visual inspection
    - Ion trap mass spectrometer
    - Neutron spectrometry
    - Potasium motor from lander or rover (burns with water, infraredimaging)
    - Mechanical surface properties (look at rover tracks)
    - X-ray Flouresence, X-ray diffraction
    - Accoustic/seismic sensing
- Pre-requisites
  - Polar lunar comsats
- Description
  - In-situ investigation of areas of greatest interest as determined by Missions 1 & 2
  - Large lander to seriously map 5 km radius at bottom of crater.
  - Swarm of 10 medium (100 kg) rovers
  - 2,000+ kg landed payload
  - 1,000 kwh power using Integrated Vehicle Fluids burning residual LH2/LO2 from lander
  - Central lab on lander for testing samples that rovers don't do insitu
- Required technology development
- Timeframe: 2023-2026
- ROM cost: $970M

Team 7



Space Resources Roundtable

LEAG

LUNAR EXPLORATION ANALYSIS GROUP

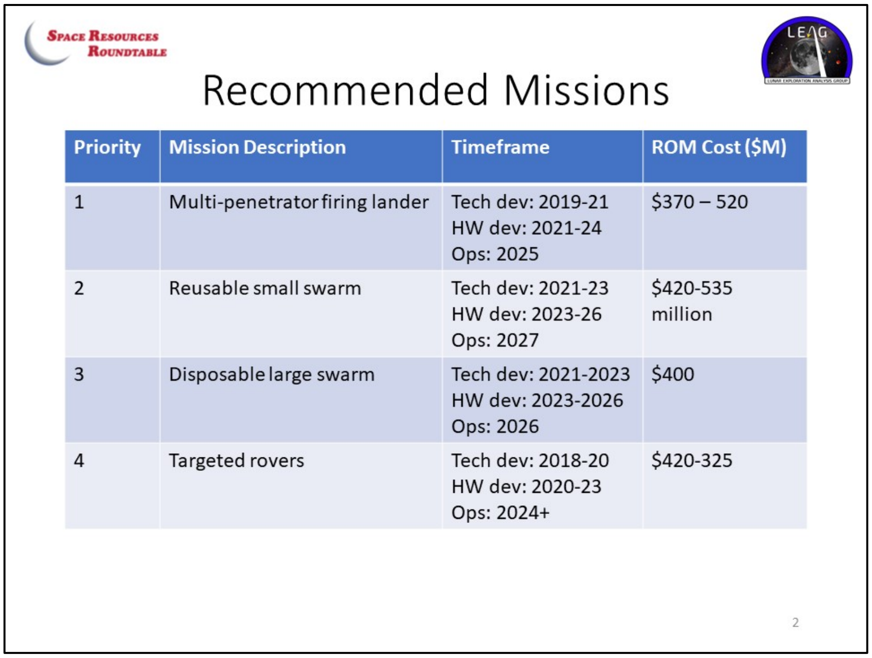
Lunar Polar Prospecting Workshop

Team #7

Rover/Sampling/Analysis

DAY 2

June 15, 2018



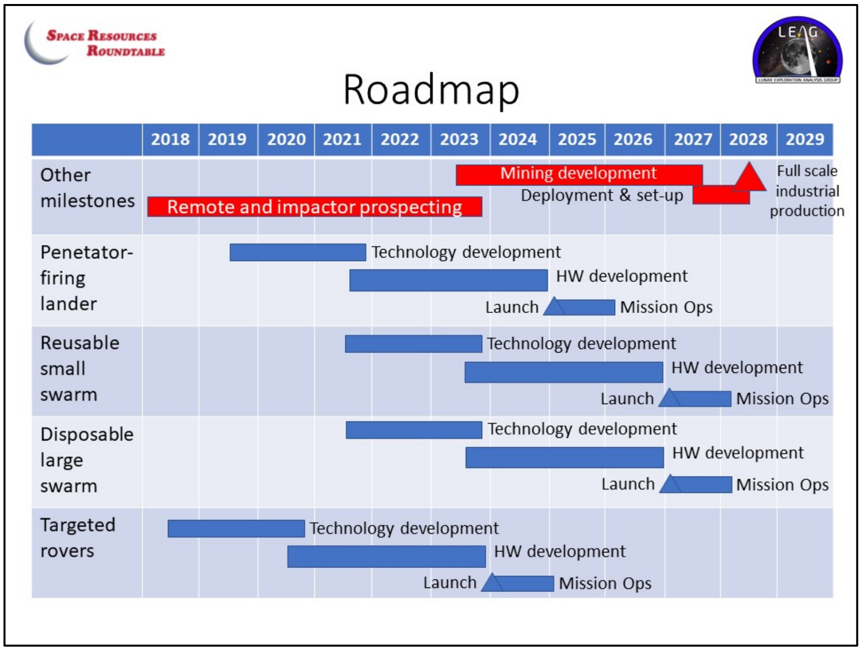
Space Resources Roundtable

LEAG

Recommended Missions

Priority	Mission Description	Timeframe	ROM Cost ($M)
1	Multi-penetrator firing lander	Tech dev: 2019-21 HW dev: 2021-24 Ops: 2025	$370 – 520
2	Reusable small swarm	Tech dev: 2021-23 HW dev: 2023-26 Ops: 2027	$420-535 million
3	Disposable large swarm	Tech dev: 2021-2023 HW dev: 2023-2026 Ops: 2026	$400
4	Targeted rovers	Tech dev: 2018-20 HW dev: 2020-23 Ops: 2024+	$420-325

2



Roadmap

2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

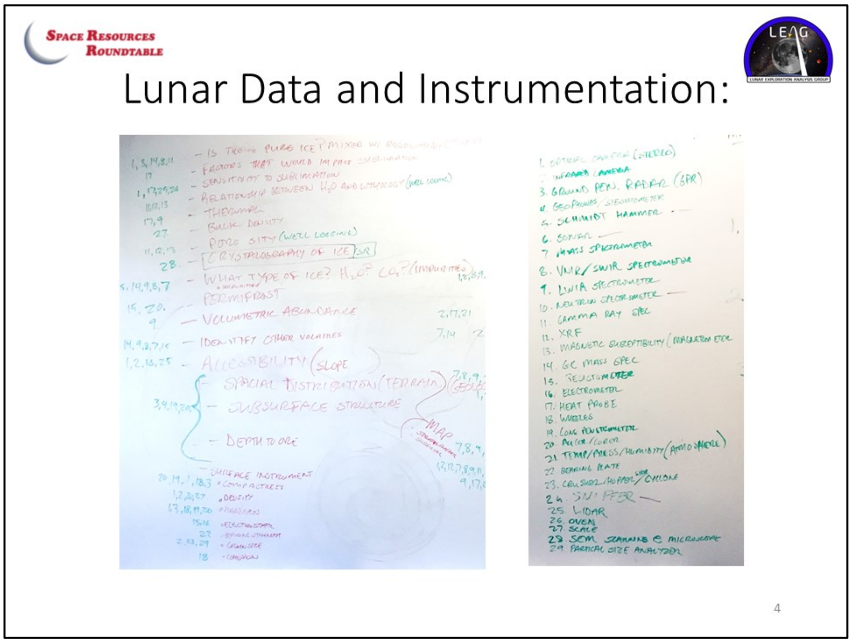
Other milestones
Mining development
Remote and impactor prospecting
Deployment & set-up
Full scale industrial production

Penetrator-firing lander
Technology development
HW development
Launch
Mission Ops

Reusable small swarm
Technology development
HW development
Launch
Mission Ops

Disposable large swarm
Technology development
HW development
Launch
Mission Ops

Targeted rovers
Technology development
HW development
Launch
Mission Ops

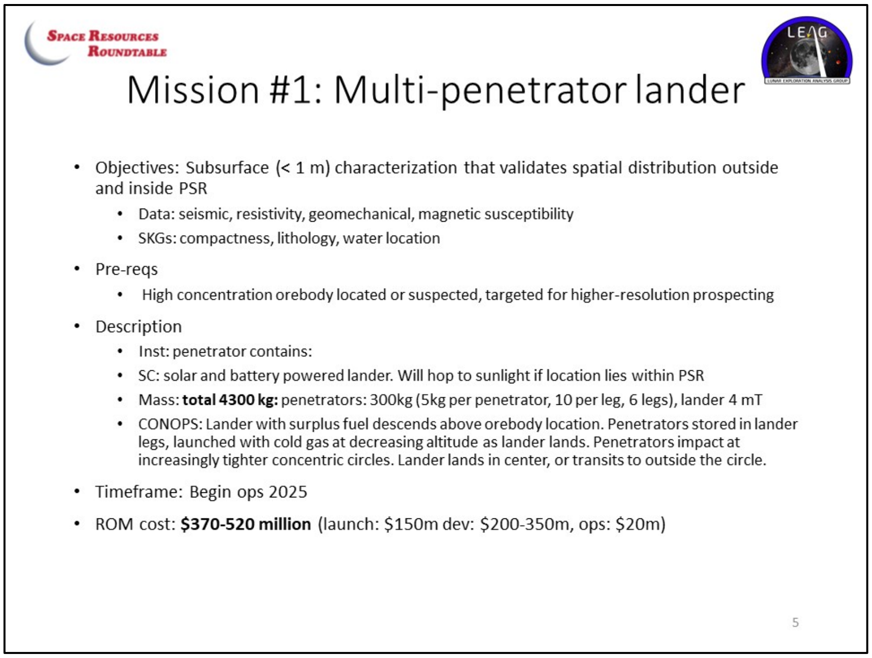


Lunar Data and Instrumentation:

- IS THERE PURE ICE? MIXED W/ REGOLITH
1,3,14,8,11 17 - FACTORS THAT WOULD IMPACT SUBLIMATION
- SENSITIVITY TO SUBLIMATION
1,17,25,26 - RELATIONSHIP BETWEEN H_2O AND LITHOLOGY (WELL LOGGING)
11,12,13 - THERMAL
17,9 - BULK DENSITY
27 - POROSITY (WELL LOGGING)
11,12,13 - CRYSTALLOGRAPHY OF ICE SR
28. - WHAT TYPE OF ICE? H_2O? CO_2? (IMPURITIES) 1,2,8,9.
5,14,9,8,7 PERMAFROST
15,20. 9 - VOLUMETRIC ABUNDANCE 2,17,21
14,9,8,7,15 - IDENTIFY OTHER VOLATILES 7,14
1,2,18,25 - ACCESSIBILITY (SLOPE)
3,4,19,20 - SPACIAL DISTRIBUTION (TERRAIN) (GEOL 7,8,9,
- SUBSURFACE STRUCTURE
- DEPTH TO ORE
MAP 7,8,9,
- SURFACE INSTRUMENT 1,2,12,7,8,9,11, 9,17,
20,19,1,18,3 • COMPACTNESS
1,2,20,27 • DENSITY
13,18,19,20 • HARDNESS
15,16 • ELECTROSTATIC
22 • BEARING STRENGTH
2,23,29 • GRAIN SIZE
18 • COHESION

1. OPTICAL CAMERA (STEREO)
2. INFRARED CAMERA
3. GROUND PEN. RADAR (GPR)
4. GEOPHONES / SEISMOMETER
5. SCHMIDT HAMMER
6. SONAR
7. MASS SPECTROMETER
8. VNIR / SWIR SPECTROMETER
9. LWIR SPECTROMETER
10. NEUTRON SPECTROMETER
11. GAMMA RAY SPEC
12. XRF
13. MAGNETIC SUSCEPTIBILITY (MAGNETOMETER
14. GC MASS SPEC
15. RESISTOMETER
16. ELECTROMETER
17. HEAT PROBE
18. WHEELS
19. CONE PENETROMETER
20. AUGER / CORER
21. TEMP/PRESS/HUMIDITY (ATMOSPHERE)
22. BEARING PLATE
23. CRUSHER/HOPPER/SIEVE/CYCLONE
24. SNIFFER
25. LIDAR
26. OVEN
27. SCALE
28. SEM SCANNING E MICROSCOPE
29. PARTICAL SIZE ANALYZER

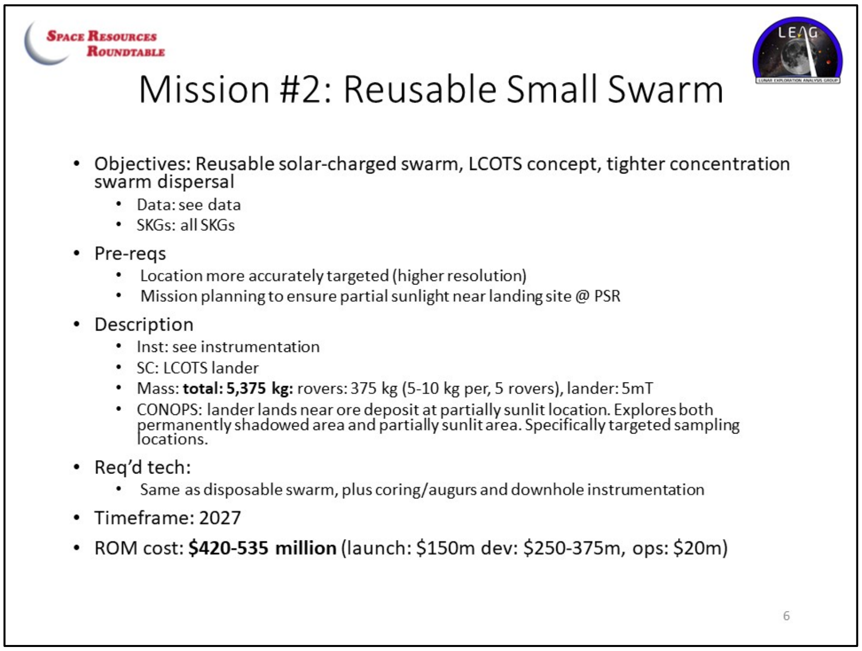
4



Mission #1: Multi-penetrator lander

- Objectives: Subsurface (< 1 m) characterization that validates spatial distribution outside and inside PSR
  - Data: seismic, resistivity, geomechanical, magnetic susceptibility
  - SKGs: compactness, lithology, water location
- Pre-reqs
  - High concentration orebody located or suspected, targeted for higher-resolution prospecting
- Description
  - Inst: penetrator contains:
  - SC: solar and battery powered lander. Will hop to sunlight if location lies within PSR
  - Mass: **total 4300 kg:** penetrators: 300kg (5kg per penetrator, 10 per leg, 6 legs), lander 4 mT
  - CONOPS: Lander with surplus fuel descends above orebody location. Penetrators stored in lander legs, launched with cold gas at decreasing altitude as lander lands. Penetrators impact at increasingly tighter concentric circles. Lander lands in center, or transits to outside the circle.
- Timeframe: Begin ops 2025
- ROM cost: **$370-520 million** (launch: $150m dev: $200-350m, ops: $20m)

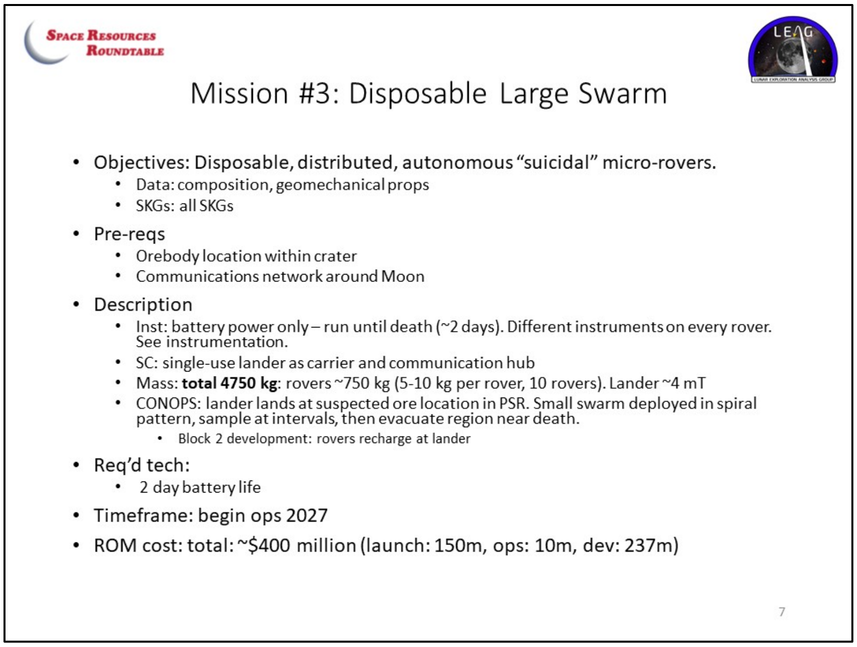
5



Mission #2: Reusable Small Swarm

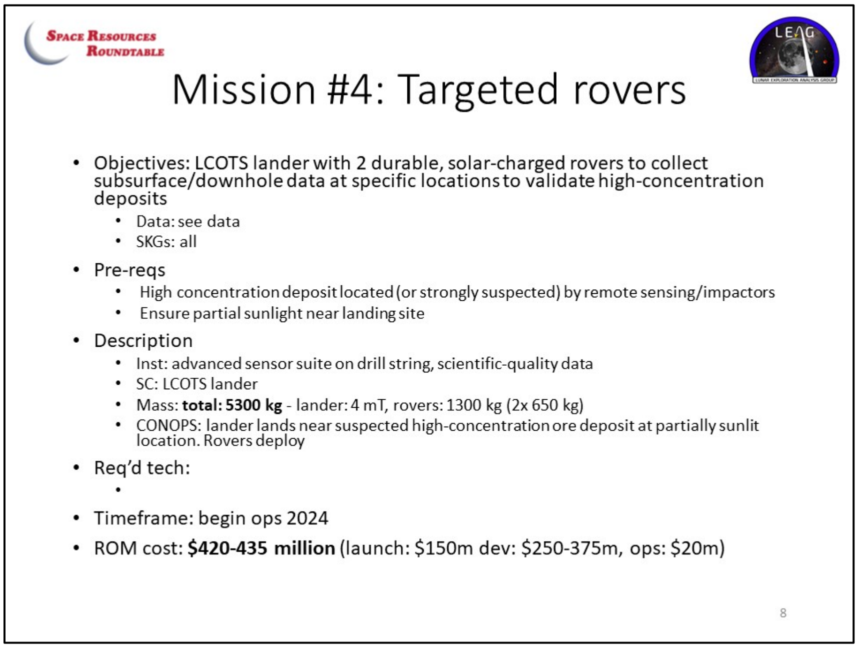
- Objectives: Reusable solar-charged swarm, LCOTS concept, tighter concentration swarm dispersal
  - Data: see data
  - SKGs: all SKGs
- Pre-reqs
  - Location more accurately targeted (higher resolution)
  - Mission planning to ensure partial sunlight near landing site @ PSR
- Description
  - Inst: see instrumentation
  - SC: LCOTS lander
  - Mass: **total: 5,375 kg:** rovers: 375 kg (5-10 kg per, 5 rovers), lander: 5mT
  - CONOPS: lander lands near ore deposit at partially sunlit location. Explores both permanently shadowed area and partially sunlit area. Specifically targeted sampling locations.
- Req'd tech:
  - Same as disposable swarm, plus coring/augurs and downhole instrumentation
- Timeframe: 2027
- ROM cost: **$420-535 million** (launch: $150m dev: $250-375m, ops: $20m)

6



Mission #3: Disposable Large Swarm

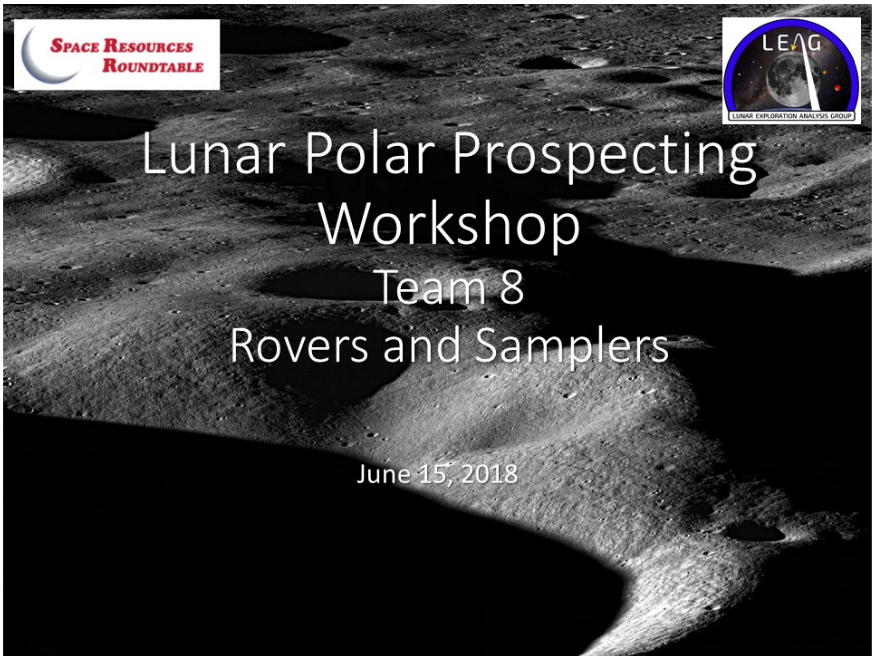
- Objectives: Disposable, distributed, autonomous "suicidal" micro-rovers.
  - Data: composition, geomechanical props
  - SKGs: all SKGs
- Pre-reqs
  - Orebody location within crater
  - Communications network around Moon
- Description
  - Inst: battery power only – run until death (~2 days). Different instruments on every rover. See instrumentation.
  - SC: single-use lander as carrier and communication hub
  - Mass: **total 4750 kg**: rovers ~750 kg (5-10 kg per rover, 10 rovers). Lander ~4 mT
  - CONOPS: lander lands at suspected ore location in PSR. Small swarm deployed in spiral pattern, sample at intervals, then evacuate region near death.
    - Block 2 development: rovers recharge at lander
- Req'd tech:
  - 2 day battery life
- Timeframe: begin ops 2027
- ROM cost: total: ~$400 million (launch: 150m, ops: 10m, dev: 237m)



Mission #4: Targeted rovers

- Objectives: LCOTS lander with 2 durable, solar-charged rovers to collect subsurface/downhole data at specific locations to validate high-concentration deposits
  - Data: see data
  - SKGs: all
- Pre-reqs
  - High concentration deposit located (or strongly suspected) by remote sensing/impactors
  - Ensure partial sunlight near landing site
- Description
  - Inst: advanced sensor suite on drill string, scientific-quality data
  - SC: LCOTS lander
  - Mass: **total: 5300 kg** - lander: 4 mT, rovers: 1300 kg (2x 650 kg)
  - CONOPS: lander lands near suspected high-concentration ore deposit at partially sunlit location. Rovers deploy
- Req'd tech:
  -
- Timeframe: begin ops 2024
- ROM cost: **$420-435 million** (launch: $150m dev: $250-375m, ops: $20m)

Team 8



SPACE RESOURCES ROUNDTABLE

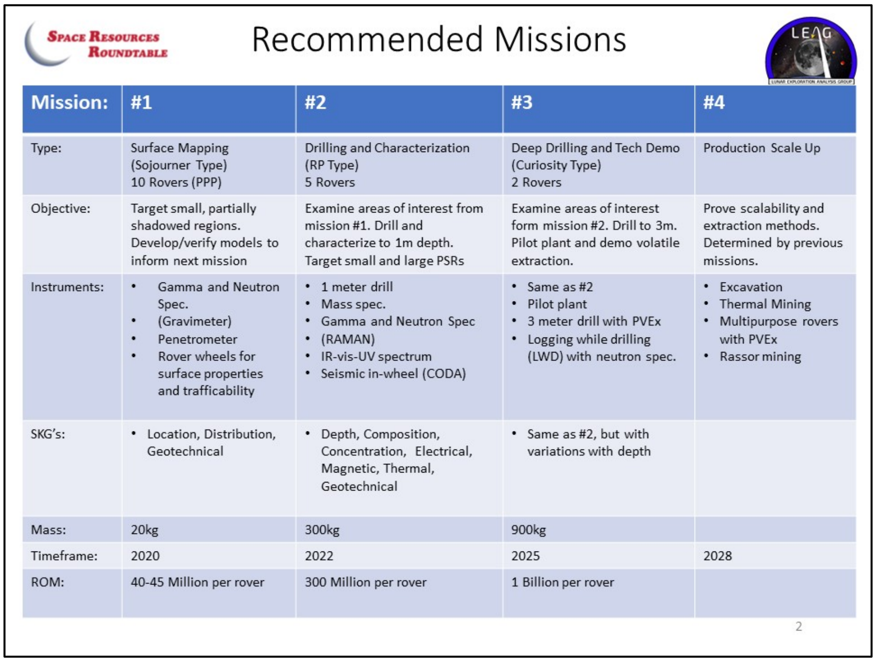
LUNAR EXPLORATION ANALYSIS GROUP

Lunar Polar Prospecting Workshop

Team 8

Rovers and Samplers

June 15, 2018

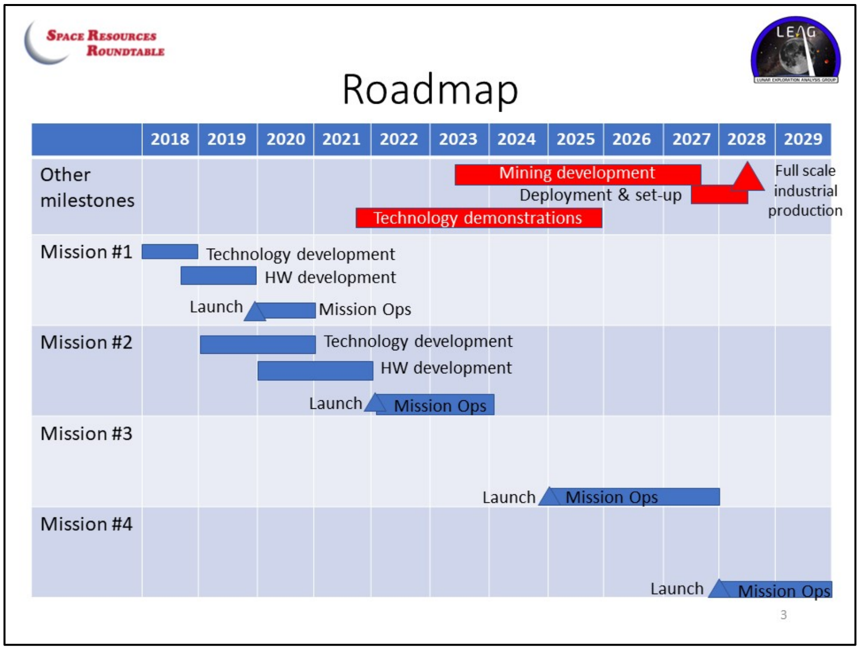


SPACE RESOURCES ROUNDTABLE

Recommended Missions

Mission:	#1	#2	#3	#4
Type:	Surface Mapping (Sojourner Type) 10 Rovers (PPP)	Drilling and Characterization (RP Type) 5 Rovers	Deep Drilling and Tech Demo (Curiosity Type) 2 Rovers	Production Scale Up
Objective:	Target small, partially shadowed regions. Develop/verify models to inform next mission	Examine areas of interest from mission #1. Drill and characterize to 1m depth. Target small and large PSRs	Examine areas of interest form mission #2. Drill to 3m. Pilot plant and demo volatile extraction.	Prove scalability and extraction methods. Determined by previous missions.
Instruments:	• Gamma and Neutron Spec. • (Gravimeter) • Penetrometer • Rover wheels for surface properties and trafficability	• 1 meter drill • Mass spec. • Gamma and Neutron Spec • (RAMAN) • IR-vis-UV spectrum • Seismic in-wheel (CODA)	• Same as #2 • Pilot plant • 3 meter drill with PVEx • Logging while drilling (LWD) with neutron spec.	• Excavation • Thermal Mining • Multipurpose rovers with PVEx • Rassor mining
SKG's:	• Location, Distribution, Geotechnical	• Depth, Composition, Concentration, Electrical, Magnetic, Thermal, Geotechnical	• Same as #2, but with variations with depth	
Mass:	20kg	300kg	900kg	
Timeframe:	2020	2022	2025	2028
ROM:	40-45 Million per rover	300 Million per rover	1 Billion per rover	

2



Roadmap

2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

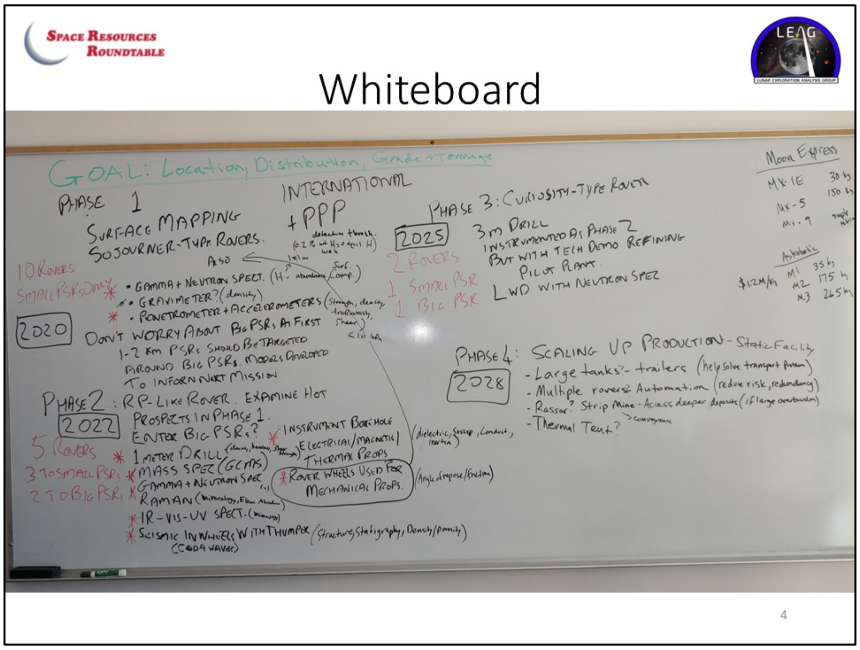
Other milestones
- Mining development
- Deployment & set-up
- Technology demonstrations
- Full scale industrial production

Mission #1
- Technology development
- HW development
- Launch
- Mission Ops

Mission #2
- Technology development
- HW development
- Launch
- Mission Ops

Mission #3
- Launch
- Mission Ops

Mission #4
- Launch
- Mission Ops



Whiteboard

GOAL: Location, Distribution, Grade + Tonnage

PHASE 1

INTERNATIONAL + PPP

SURFACE MAPPING
SOJOURNER-TYPE ROVERS.
ALSO
10 ROVERS
SMALL PSRs ONLY
2020
- ✱ GAMMA + NEUTRON SPECT. (H abundance 1x1 km, detection thresh. (0.2 % wt H₂O equiv. H), Surf. Comp.)
- ∅ GRAVIMETER? (density)
- ✱ PENETROMETER + ACCELEROMETERS (Strength, density, trafficability, Shear) <10 kPa

DON'T WORRY ABOUT BIG PSRs AT FIRST
1-2 KM PSRs SHOULD BE TARGETED
AROUND BIG PSRs. MODELS DEVELOPED
TO INFORM NEXT MISSION

PHASE 2: RP-LIKE ROVER. EXAMINE HOT PROSPECTS IN PHASE 1.
2022
ENTER BIG PSRs?
5 ROVERS
3 TO SMALL PSRs
2 TO BIG PSRs
- ✱ 1 METER DRILL (density, hardness, shear strength)
- ✱ MASS SPEC (GCMS)
- ✱ GAMMA + NEUTRON SPEC
- RAMAN (mineralogy, Elem. Abundance)
- ✱ IR-VIS-UV SPECT. (mineralogy)
- ✱ SEISMIC IN WHEELS WITH THUMPER (CODA WAVES) (Structure, Statigraphy, Density/porosity)
- ✱ INSTRUMENT BOREHOLE ELECTRICAL/MAGNETIC THERMAL PROPS (dielectric, suscep., Conduct., inertia)
- ✱ ROVER WHEELS USED FOR MECHANICAL PROPS. (Angle of repose/friction)

PHASE 3: CURIOSITY-TYPE ROVER
2025
2 ROVERS
1 SMALL PSR
1 BIG PSR
3 m DRILL
INSTRUMENTED AS PHASE 2
BUT WITH TECH DEMO REFINING
PILOT PLANT.
LWD WITH NEUTRON SPEC

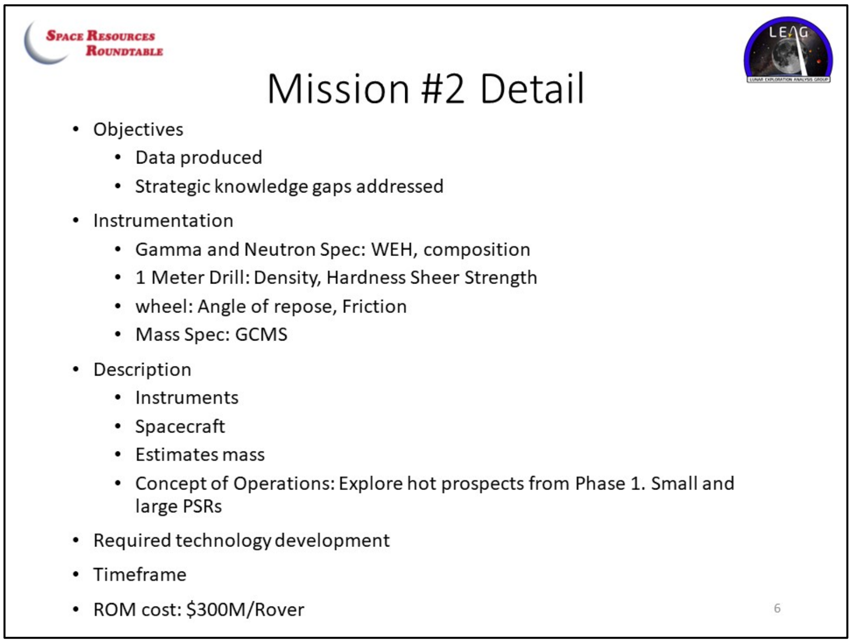
PHASE 4: SCALING UP PRODUCTION - Static Facility
2028
- Large tanks? - trailers (help solve transport problem)
- Multiple rovers & Automation (reduce risk, redundancy)
- Rassor? Strip Mine - Access deeper deposits (if large overburden) > conveyance
- Thermal Tent?

Moon Express
MX-1E 30 kg
MX-5 150 kg
MX-9 [illegible]

Astrobotic
$1.2M/kg
M1 35 kg
M2 175 kg
M3 265 kg

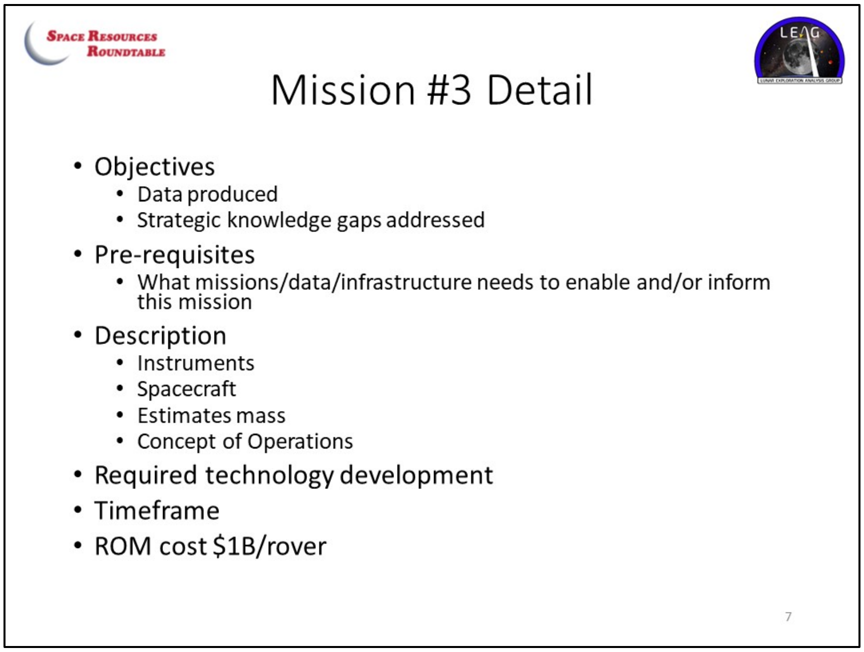
Mission #1 – Surface Mapping

- Objectives
- Instrumentation
  - Gamma and Neutron Spec: H abundance and composition
  - Penetrometer: Strength, density, and trafficability,
- Description
  - Instruments: Seismic in-wheel, gamma and neutron spectrometer, gravimeter, penetrometer
  - Spacecraft: Rover, Sojourner type
  - Mass: 20kg
- Con Ops: Most to small PSRs, 1-2 to explore larger PSRs (e.g., Peary
- Commercial off the shelf Technology
- Time Frame: 2020
- $40 to $45 Million per rover



Mission #2 Detail

- Objectives
  - Data produced
  - Strategic knowledge gaps addressed
- Instrumentation
  - Gamma and Neutron Spec: WEH, composition
  - 1 Meter Drill: Density, Hardness Sheer Strength
  - wheel: Angle of repose, Friction
  - Mass Spec: GCMS
- Description
  - Instruments
  - Spacecraft
  - Estimates mass
  - Concept of Operations: Explore hot prospects from Phase 1. Small and large PSRs
- Required technology development
- Timeframe
- ROM cost: $300M/Rover



Mission #3 Detail

- Objectives
  - Data produced
  - Strategic knowledge gaps addressed
- Pre-requisites
  - What missions/data/infrastructure needs to enable and/or inform this mission
- Description
  - Instruments
  - Spacecraft
  - Estimates mass
  - Concept of Operations
- Required technology development
- Timeframe
- ROM cost $1B/rover

Mission #4 Detail

- Objectives
  - Data produced
  - Strategic knowledge gaps addressed
- Pre-requisites
  - What missions/data/infrastructure needs to enable and/or inform this mission
- Description
  - Instruments
  - Spacecraft
  - Estimates mass
  - Concept of Operations
- Required technology development
- Timeframe: 2028
- ROM cost ??

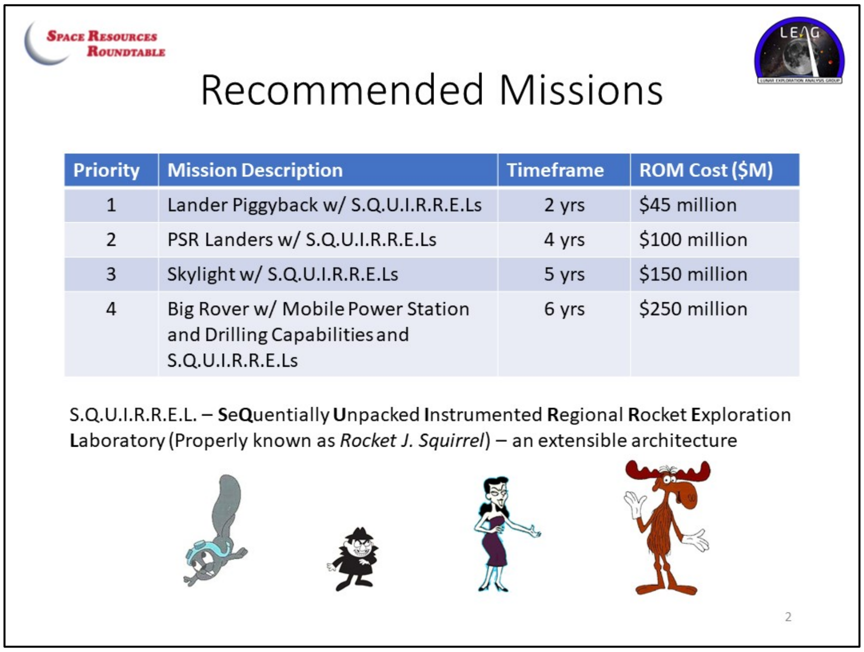
Team 9

Lunar Polar Prospecting Workshop

Team 9

Landers and Rovers

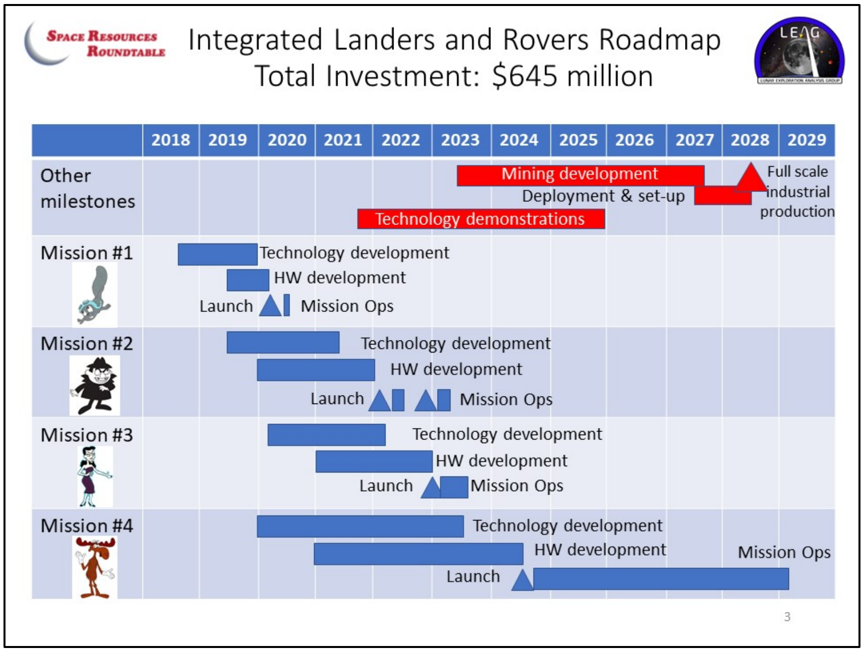
June 15, 2018



Recommended Missions

Priority	Mission Description	Timeframe	ROM Cost ($M)
1	Lander Piggyback w/ S.Q.U.I.R.R.E.Ls	2 yrs	$45 million
2	PSR Landers w/ S.Q.U.I.R.R.E.Ls	4 yrs	$100 million
3	Skylight w/ S.Q.U.I.R.R.E.Ls	5 yrs	$150 million
4	Big Rover w/ Mobile Power Station and Drilling Capabilities and S.Q.U.I.R.R.E.Ls	6 yrs	$250 million

S.Q.U.I.R.R.E.L. – **SeQ**uentially **U**npacked **I**nstrumented **R**egional **R**ocket **E**xploration **L**aboratory (Properly known as *Rocket J. Squirrel*) – an extensible architecture



Space Resources Roundtable

Integrated Landers and Rovers Roadmap
Total Investment: $645 million

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029

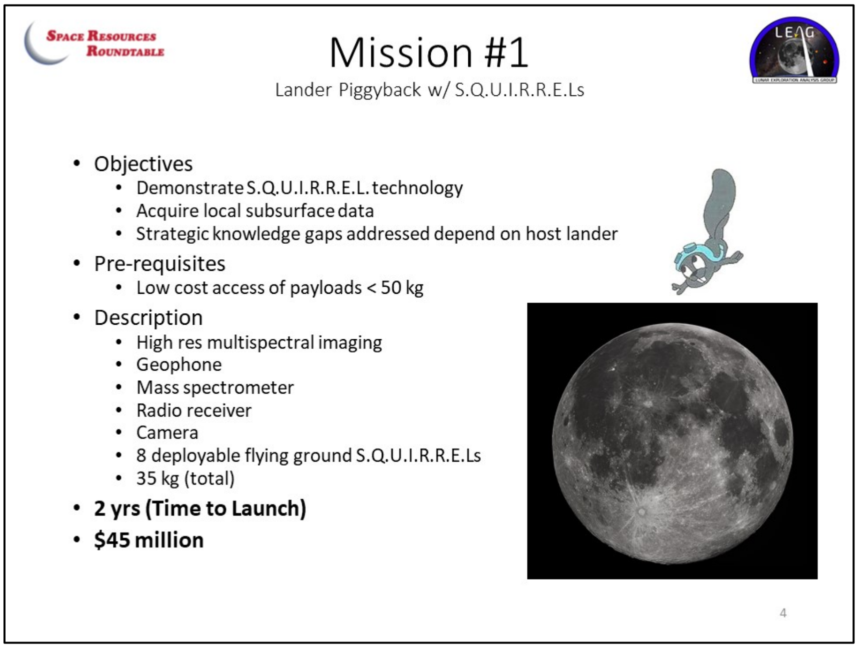
Other milestones
Mining development
Deployment & set-up
Full scale industrial production
Technology demonstrations

Mission #1
Technology development
HW development
Launch
Mission Ops

Mission #2
Technology development
HW development
Launch
Mission Ops

Mission #3
Technology development
HW development
Launch
Mission Ops

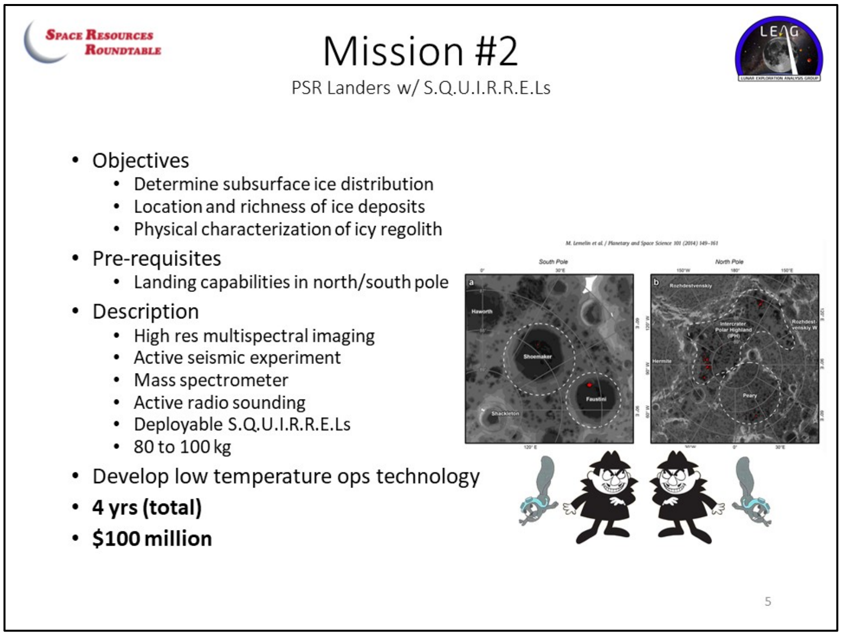
Mission #4
Technology development
HW development
Mission Ops
Launch



Space Resources Roundtable

Mission #1
Lander Piggyback w/ S.Q.U.I.R.R.E.Ls

- Objectives
  - Demonstrate S.Q.U.I.R.R.E.L. technology
  - Acquire local subsurface data
  - Strategic knowledge gaps addressed depend on host lander
- Pre-requisites
  - Low cost access of payloads < 50 kg
- Description
  - High res multispectral imaging
  - Geophone
  - Mass spectrometer
  - Radio receiver
  - Camera
  - 8 deployable flying ground S.Q.U.I.R.R.E.Ls
  - 35 kg (total)
- **2 yrs (Time to Launch)**
- **$45 million**



Mission #2

PSR Landers w/ S.Q.U.I.R.R.E.Ls

- Objectives
  - Determine subsurface ice distribution
  - Location and richness of ice deposits
  - Physical characterization of icy regolith
- Pre-requisites
  - Landing capabilities in north/south pole
- Description
  - High res multispectral imaging
  - Active seismic experiment
  - Mass spectrometer
  - Active radio sounding
  - Deployable S.Q.U.I.R.R.E.Ls
  - 80 to 100 kg
- Develop low temperature ops technology
- **4 yrs (total)**
- **$100 million**

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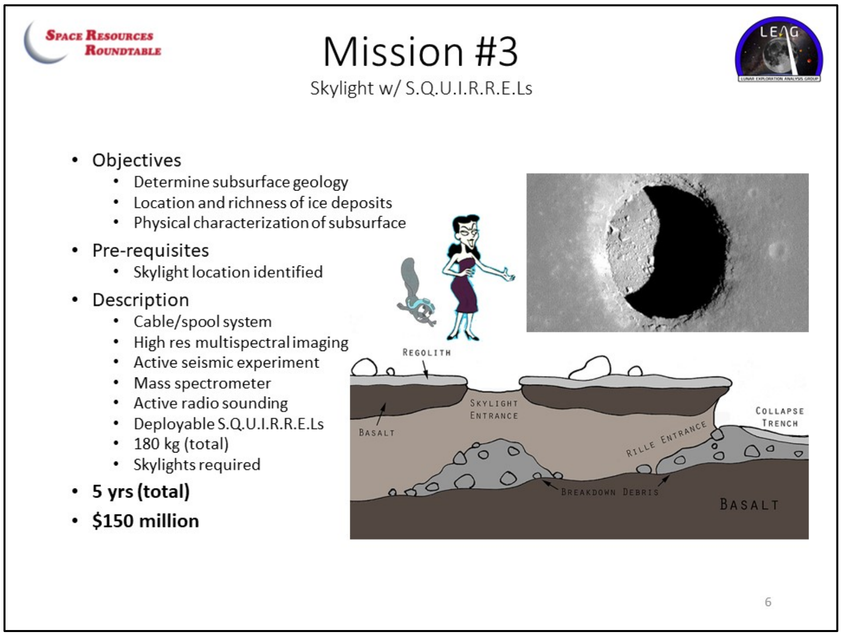
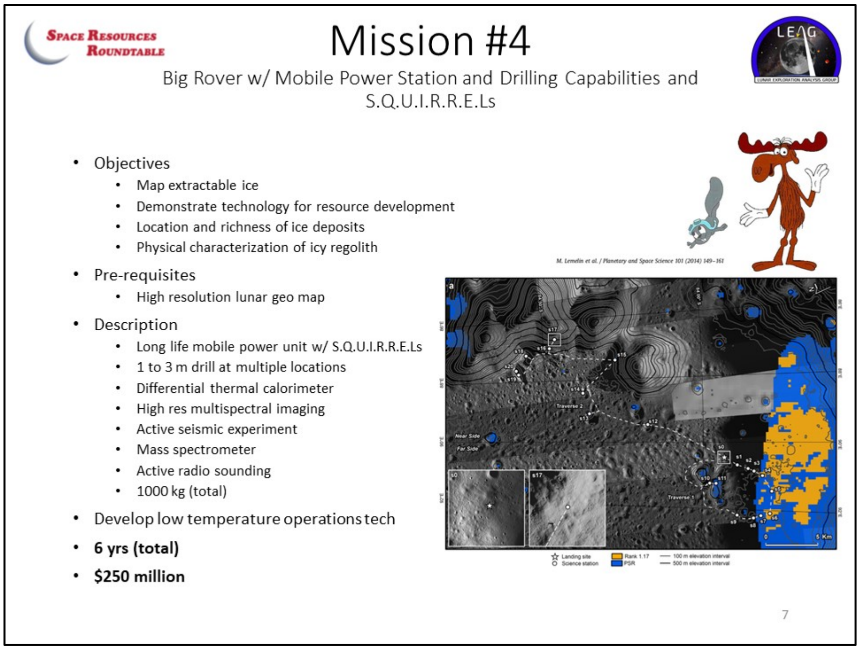


Mission #3

Skylight w/ S.Q.U.I.R.R.E.Ls

- Objectives
  - Determine subsurface geology
  - Location and richness of ice deposits
  - Physical characterization of subsurface
- Pre-requisites
  - Skylight location identified
- Description
  - Cable/spool system
  - High res multispectral imaging
  - Active seismic experiment
  - Mass spectrometer
  - Active radio sounding
  - Deployable S.Q.U.I.R.R.E.Ls
  - 180 kg (total)
  - Skylights required
- **5 yrs (total)**
- **$150 million**



Mission #4

Big Rover w/ Mobile Power Station and Drilling Capabilities and S.Q.U.I.R.R.E.Ls

- Objectives
  - Map extractable ice
  - Demonstrate technology for resource development
  - Location and richness of ice deposits
  - Physical characterization of icy regolith
- Pre-requisites
  - High resolution lunar geo map
- Description
  - Long life mobile power unit w/ S.Q.U.I.R.R.E.Ls
  - 1 to 3 m drill at multiple locations
  - Differential thermal calorimeter
  - High res multispectral imaging
  - Active seismic experiment
  - Mass spectrometer
  - Active radio sounding
  - 1000 kg (total)
- Develop low temperature operations tech
- **6 yrs (total)**
- **$250 million**

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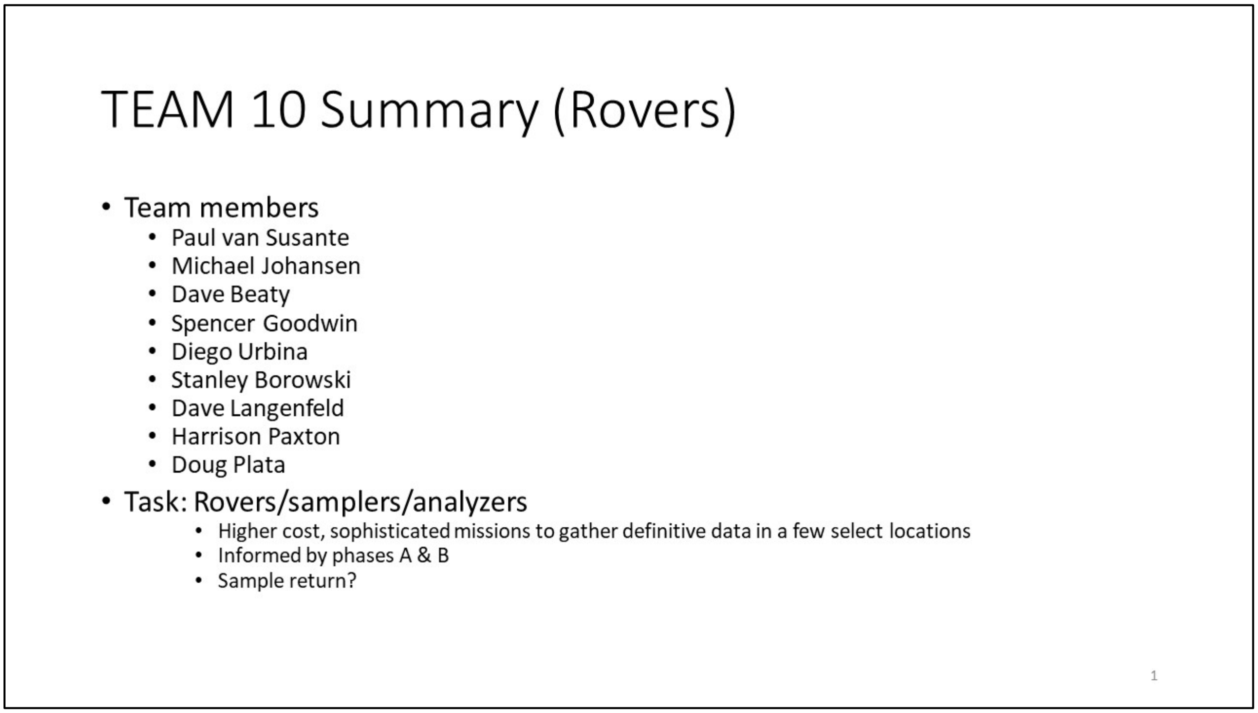
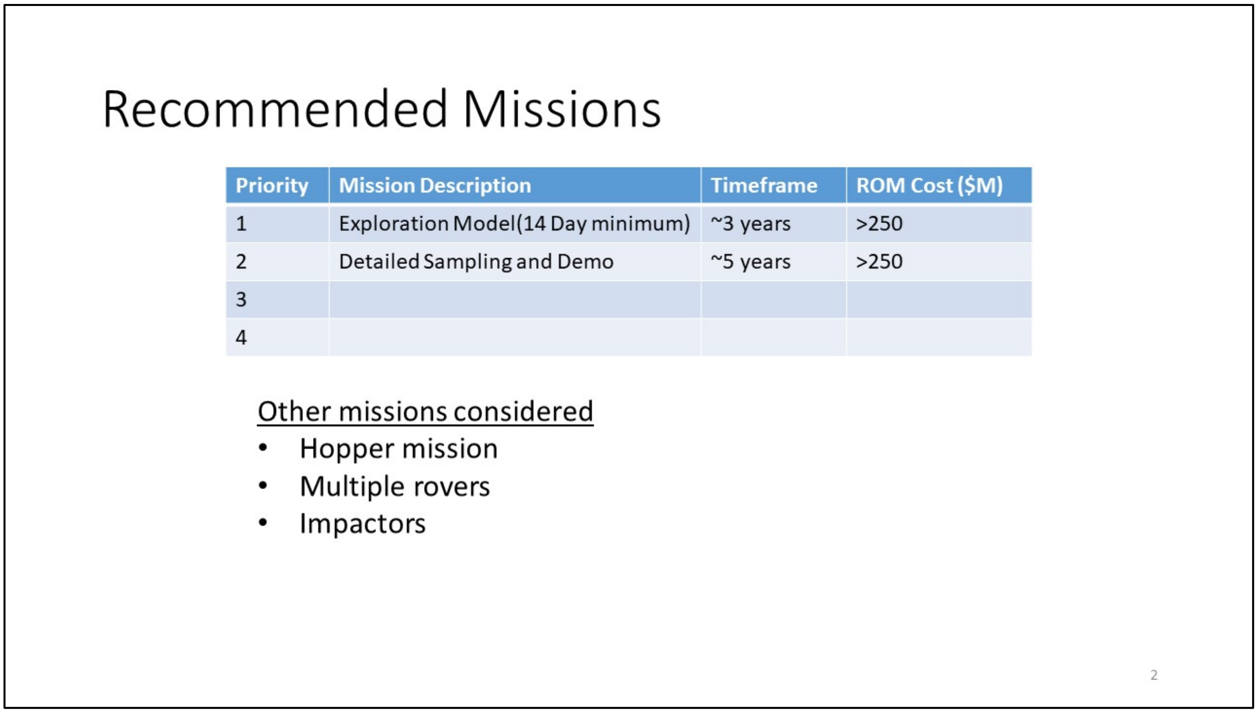
Team 10



TEAM 10 Summary (Rovers)

- Team members
  - Paul van Susante
  - Michael Johansen
  - Dave Beaty
  - Spencer Goodwin
  - Diego Urbina
  - Stanley Borowski
  - Dave Langenfeld
  - Harrison Paxton
  - Doug Plata
- Task: Rovers/samplers/analyzers
  - Higher cost, sophisticated missions to gather definitive data in a few select locations
  - Informed by phases A & B
  - Sample return?

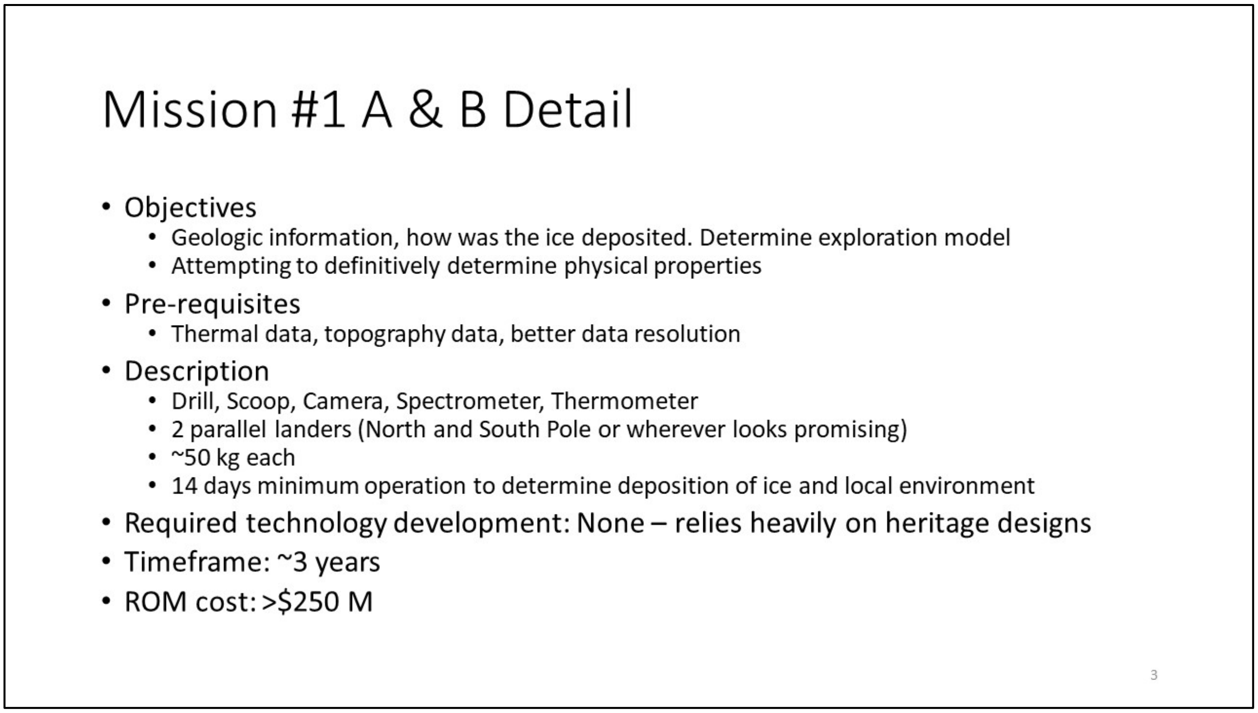


Recommended Missions

Priority	Mission Description	Timeframe	ROM Cost ($M)
1	Exploration Model(14 Day minimum)	~3 years	>250
2	Detailed Sampling and Demo	~5 years	>250
3			
4			

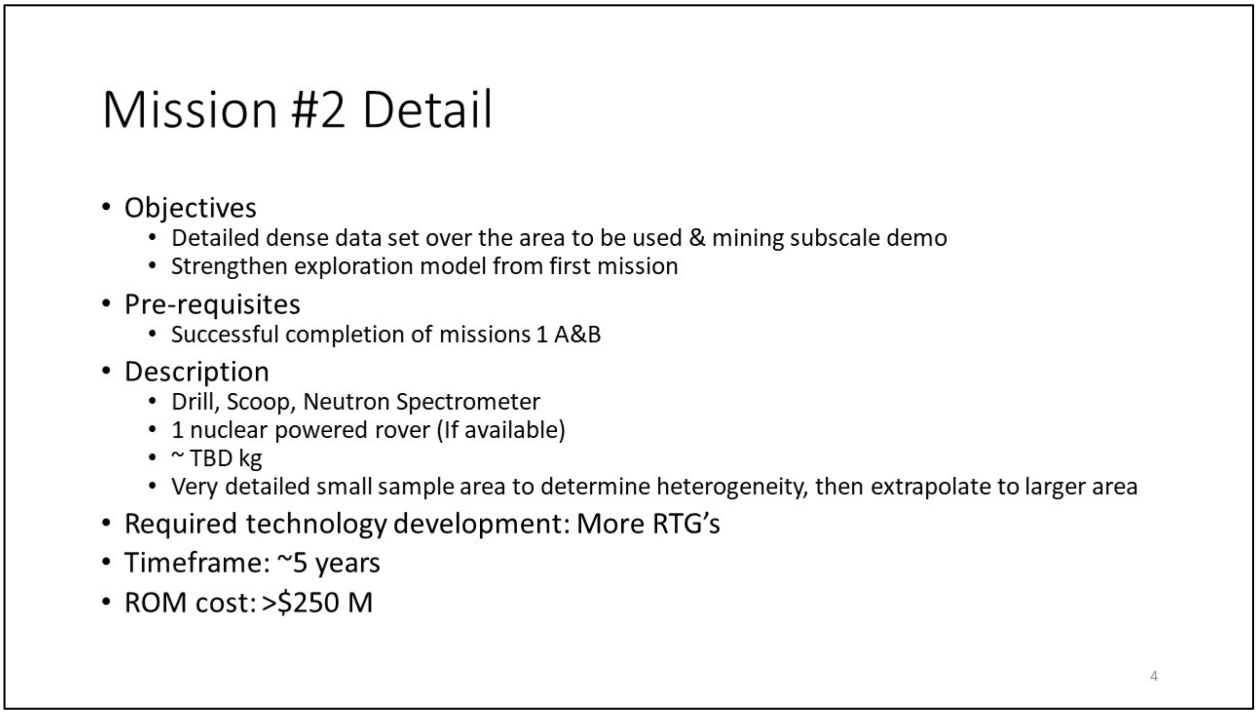
Other missions considered

- Hopper mission
- Multiple rovers
- Impactors



Mission #1 A & B Detail

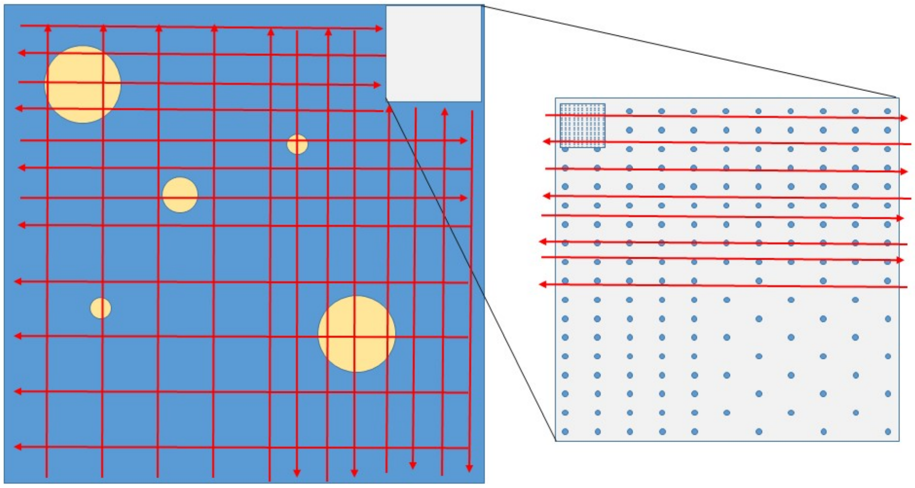
- Objectives
  - Geologic information, how was the ice deposited. Determine exploration model
  - Attempting to definitively determine physical properties
- Pre-requisites
  - Thermal data, topography data, better data resolution
- Description
  - Drill, Scoop, Camera, Spectrometer, Thermometer
  - 2 parallel landers (North and South Pole or wherever looks promising)
  - ~50 kg each
  - 14 days minimum operation to determine deposition of ice and local environment
- Required technology development: None – relies heavily on heritage designs
- Timeframe: ~3 years
- ROM cost: >$250 M



Mission #2 Detail

- Objectives
  - Detailed dense data set over the area to be used & mining subscale demo
  - Strengthen exploration model from first mission
- Pre-requisites
  - Successful completion of missions 1 A&B
- Description
  - Drill, Scoop, Neutron Spectrometer
  - 1 nuclear powered rover (If available)
  - ~ TBD kg
  - Very detailed small sample area to determine heterogeneity, then extrapolate to larger area
- Required technology development: More RTG’s
- Timeframe: ~5 years
- ROM cost: >$250 M

Drill plus neutron spectrometer



- Design for Experiment

Roadmap