Rapid Response Report

LEAG Science Activities and Site Selection Specific Action Team

Charge from NASA
Participants
Principal conclusions
More Detailed Analysis:
    Lunar Resource Utilization (ISRU)
    Biology
    Geology
    Geophysics
    Astrobiology
    Deep Field Astronomy
    Low Frequency Radio Astronomy
    Observing Earth and Environs
Qualitative Assessment of User Needs

Charge to SASS-SAT

LEAG was asked to form a quick-acting Specific Action Team (SAT) to analyze science issues that could drive human mission architectures. The boundaries are that there will be sorties first (3-7 days), perhaps three of them, followed by an outpost (30-90 days, or longer). The SAT was asked to address these questions:

1. What sites are most important for human sorties?
2. What are the most important science activities at those sites (lunar science, biology, astronomy, ISRU, etc. are all in play). Assume that the science can be accomplished in a week and that there will be no requirement to return to a site.
3. How should NASA select an outpost site, and should the process be coupled to the sortie-class missions that precede it?
4. What science objectives must humans accomplish at an Outpost mission? NASA requests a strong rationale for the highest priority science and identification of any unique or groundbreaking science.
5. What operational requirements are there for those high-priority science activities, for both sorties and outpost? What are the mobility requirements? What are the relative roles of humans and robots, how much teleoperation vs EVA? Is there a role for rovers after astronauts leave a specific site? What do the science activities imply for power requirements on the lunar surface?

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Lunar Science and Exploration

- The human exploration program advances science at every step:
  - Human sorties would offer new opportunities for a broad range of scientific studies
  - Sustained human presence at a lunar outpost opens new scientific vistas for cutting edge science
  - Robotic and telerobotic missions enhance science return
- The science of the rocks and regolith of the moon is the foundation for Lunar Resource assessment
- Significant synergism exists among types of scientific studies
- Well integrated science objectives will maximize scientific return

Sustained Human Presence…

…Is important for many scientific studies:

- Long-duration science studies (lunar geology and geophysics, astrobiology, biological studies)
- Global access for geology and geophysics, servicing astronomical observatories, biological science
- Contamination studies for planetary protection

…Requires use of lunar resources

- Fuel/power for surface science operations (including robotic sample returns, rapid transport of humans to sites far from outpost)
- Raw ingredients for life support and outpost maintenance
- Commercial possibilities could lead to sustained lunar activities

…Requires understanding the integrated biological effects of dust, low gravity, and radiation

…Develops and demonstrates capabilities for people to go to Mars

Significant Scientific Advances

- Bombardment of the Earth: Consequences for Life
  - Moon uniquely records bombardment history of inner Solar System; still poorly understood.
  - Duration and intensity of “late heavy bombardment” of early Earth and Mars is key to understanding early environments and life, including timing of “impact frustration” of life’s origins.
  - Episodicity of later impactor flux and impactor-induced mass extinctions shaped (and will shape?) evolution of multi-cellular life.
  - Return to Moon to nail down timing of “late heavy bombardment” recommended by NRC in *The Astrophysical Context of Life*
- Lunar Interior Processes and History
  - Interior of the Moon is poorly characterized
  - Interior composition and structure is essential to determining the composition of the Moon, the dynamics of the mantle, and the Moon’s thermal history
  - Central for understanding the processes involved in lunar origin

Significant Scientific Advances

- Scientific treasure in the permanently shadowed polar environment:
  - Almost completely unexplored
  - Environment utterly unlike equatorial Moon
  - Environment is similar to conditions in interstellar space and Oort cloud (silicate grains, cosmic rays UV radiation, temperature fluctuations
  - A natural laboratory for understanding environments not accessible to us at present
- Regolith as a recorder of the Sun's history
  - Read the four-billion year record of the sun and galaxy recorded in the lunar regolith
  - Apollo data hint at nuclear processes in Sun not predicted by current models of stellar evolution

Significant Scientific Advances

- Contributions to Biomedicine
  - Lunar expedition biomedical discoveries and terrestrial biomedical advances are synergistic
  - Determine fundamental mechanisms causing genomic damage
  - Novel approaches to study & address earth-based pathogenesis and environmental health hazards
- Using the Moon’s Resources:
  - Fundamental advances in science associated with resource extraction greatly enhances human exploration capabilities on the Moon, cislunar space, and eventually for the exploration of Mars
- Astronomy:
  - Ultra deep field: Potential additional approach for observing first stars to form in the universe (beyond JWST)
  - Low frequency radio astronomy opens up new wavelength range

Robotics and Telerobotics

- Mitigates risks to human explorers and increases crew efficiency
- Many jobs can be done at least partly with robots:
  - Site surveys for astronomical facilities
  - Background measurements before human contamination
  - Assessment of volatiles in permanently shadowed regions
  - Deployment of simple geophysical and biological packages
- Robotic studies can precede human landings at sortie or outpost sites and can continue after humans leave sortie sites
- Permits interpolation and extrapolation of in-depth science accomplished by human missions
- Pre-crew emplacement of equipment and facilities, including Lunar Resource Development plants
- Telerobotics for some geologic and biological field work (astronauts safe in shielded habitat)
- Telerobotics is one component for providing global access
  - Feed forward to exploration of Mars using teleoperation from a single Mars human landing
- Telerobotics technology exists, but requires investment to use extensively on the Moon and Mars

Synergism Among Science Studies-1

- Example 1: Site selection:
  - For either sorties or outpost, a geologically diverse site is desirable
    - Numerous geological problems to work on over long period
    - Chemically and physically diverse regolith for biological studies

Example: Aristarchus plateau has unusual highland rocks, basaltic lava flows, and basaltic pyroclastic (glassy) deposits

- Diversity of geologic features of interest to all lunar scientists (but atypical in terms of global composition)
- Biology for soil hazard studies
- Buried regolith for studying solar history
- ISRU (especially the glass deposits for O_2 extraction)

Synergism Among Science Studies-2

- Example 2: General lunar science and astrobiology:

Problem	Lunar/Planetary Science	Astrobiology
Early bombardment history	Flux and composition of projectiles; test for spike in bombardment rate	Effect on origin and early evolution of life on Earth
Bombardment during the development of multi-cellular life	Flux through time; impact hazards; calibration of lunar stratigraphy	Test for episodicity in extinction events
History of the Sun	Regolith dynamics, nature of regolith-bedrock interface; engineering	Effect of solar variability on life

Synergism Among Science Studies-3

- Example 3: Need for global access and robust infrastructure
  - Deployment of a global geophysical network
  - Direct study of many geologically interesting sites
  - Astrobiological studies benefit from numerous sites to study bombardment, history of the Sun
  - Access to new types of non-terrestrial or free-space astronomical observatories for installation and servicing:
    - Optical/infrared in polar regions
    - Radio telescopes (far IR and mm wavelengths and long wavelengths, < 30 MHz) on far side (shielded from Earth RFI)

Critical Surface Activities

- Critical activities are defined by a combination of:
  - Priority of science investigation
  - Operational considerations
  - Sequence in which activities are logically done
  - Extent to which they feed forward to Mars exploration
- Activities have not been placed in priority order
- Purpose is to aid in development of reference missions

Critical Surface Activities

- Deploy biological instruments and experiments, and retrieve samples from them
  - Understanding integrated effects of radiation, low gravity, and dust on biological systems essential to sustained human present on other planets and in space
  - Understanding bioreactivity of lunar soil
  - Understanding extent of bio-organic contamination of environment helps design systems for Mars exploration
- Deploy geophysical and environmental instruments and experiments
  - Study of near subsurface important for resource extraction and basic science
  - Each landing site becomes part of a global network to understand bulk properties of the Moon
  - Evaluate lunar environment for astronomy and remote sensing observations of Earth
  - Needed for understanding low-frequency radio interference from Earth, essential for establishment of low-frequency radio telescope array

Critical Surface Activities

- Study of regolith to identify optimal site for resource extraction experiments
- Investigate physics and chemistry of ISRU processes
- Observations and sampling by humans of subsurface revealed by resource extraction equipment
  - Helps us understand the relation between variations in regolith properties and efficiency of resource extraction systems
  - Makes synergistic use of excavated materials for high-priority scientific studies

Critical Surface Activities

- Geological field studies
  - Uses human powers of observations and analysis to unravel geological history of field site
  - Obtain optimal set of samples for chemical and chronological analysis (essential to addressing major geological and astrobiological goals)
- Industrial manufacturing experiments
  - Products, not just raw materials, will be used on Moon or exported to other destinations in space
  - Ambitious scientific installations such as advanced astronomical observatories on the Moon or in space require metals for the framework and surface of mirrors
  - Specific examples:
    - Produce small prototype of liquid-mirror optical telescope
  - Sustained presence on the Moon is helped by establishing a thriving manufacturing industry

Critical Surface Activities

- Experiments in teleoperation from both lunar outpost and Earth
  - Humans should be able to go anywhere on the Moon, but:
  - Teleoperation may be the most cost-effective way of obtaining global access for geological studies
  - Time delay must be short (no more than the 2.5 second delay between Earth and Moon) to make use of human observational skills
  - Global exploration of Mars will require teleoperation of rovers placed far from an outpost
  - If rovers that carry humans are equipped for teleoperation (with autonomous control of some functions), they can be used after the crew leaves site of a sortie mission
- Test scientific experiments and techniques with application to Mars, for example:
  - Active seismic sounding
  - New instrumentation for *in situ* analysis (dust detectors, mass spectrometers for atmospheric studies)

More Detailed Analysis:

Lunar Resource Development (ISRU)
Biology
Geology
Geophysics
Astrobiology
Deep Field Astronomy
Low Frequency Radio Astronomy
Observing Earth and Environs

Lunar Resource Development: Major Goals

- Determine the abundance, form, lateral and vertical distribution of hydrogen/water deposits near poles
- Demonstrate the extraction of key components of propellant and life support consumables in-situ from lunar materials
  - Water, hydrogen and oxygen from polar deposits
  - Oxygen from regolith or volcanic glass
- Investigate the potential to produce other types of materials from regolith
  - Solar wind volatiles (e.g., hydrogen) extracted from mare regolith
  - Glass, metals, ceramic materials, solar cells
- Establish the geotechnical characteristics of lunar regolith (both polar and elsewhere) that determine the design of regolith excavation, transportation and handling systems

Lunar Resource Development: Critical Capabilities

- Sample collection systems
  - Robotic arms
  - Excavation and surface transportation vehicles
- Regolith processing systems
  - Thermal extraction at low temperatures (<100°C) for polar ice or hydrogen deposits
  - Operating at high temperatures (800°C – 1600°C) for regolith processing
- Technical capabilities to operate in permanent shadow for extended periods of time
  - Power (also a problem in equatorial regions)
  - Thermal management (also a problem in equatorial regions)
  - Materials properties at low temperature
- Manufacturing techniques for production of useful components

Lunar Resource Development: Sortie vs. Outpost Studies

- Sorties:
  - Polar location: Assess environmental difficulties of working in low sun illumination, dark and cold areas. Demonstrate operation and maintenance of ISRU equipment. Lay out optimum configuration for ISRU production systems.
  - Equatorial location: Sorties unnecessary (robotic emplacement of demonstration/production system appears possible)
- Outpost
  - Establish ISRU capability prior to initial human landing to demonstrate capability and improve operational robustness
  - Incorporate crew maintenance into ISRU architecture

Lunar Resource Development: Landing Site Criteria

- Polar hydrogen deposits:
  - Polar location on area of extended sunlight
  - Both poles are similar; smaller deposits at north pole may exist, which could be operationally easier to harvest
- Equatorial location:
  - Many locations possible on iron-rich mare surfaces
  - Pyroclastic deposits may be preferable due to ease of handling regolith (fine-grained, block-free feedstock)
  - Mature areas will have highest solar wind hydrogen/nitrogen content in regolith

Lunar Resource Development: Synergism with Other Science Approaches

- High power required; energy storage (e.g. regenerative fuel cells) benefit from H_2/O_2 production
  - Provides basis for surface transportation power systems for robotic and human traverses
- Integrate science investigations with ISRU
  - Stratigraphic distribution of H_2/H_2O in polar deposits provides information on history of volatiles on the Moon
  - Excavation of regolith at depth for ISRU combined with geological investigations
  - Most ISRU processes will not utilize larger rocks (>1 cm). Save these for other studies
- Servicing by humans
  - ISRU mechanical systems may require more servicing than science experiments
  - Provide basis for learning how to maintain surface systems
- Installation and survey by robotic systems
  - Site survey to establish outpost configuration (particularly important for polar site)
  - Geological exploration
  - Geotechnical properties determination
  - Significant production could be established before humans arrive

Lunar Resource Development: Feed Forward to Mars

- Develops and tests approaches to ISRU in unfamiliar planetary conditions
- Demonstrate effectiveness of ISRU in space transportation architectures
- Experience in handling and processing large quantities of granular material
- Advances use of telerobotic and autonomous robots, and their partnership with humans
- Perfect drilling mechanics and processes
- Develops appropriate power systems

Lunar Resource Development: Open Issues

- What is the relationship of polar volatiles to permanent shadow?
- What techniques will be needed for ISRU processing in permanently shadowed regions of the Moon?
- What are effective techniques for excavating, transportation, processing, storage, and disposal of waste from ISRU processes?
- What are the benefits of pre-positioning of ISRU assets at human outpost sites
- Are there undiscovered resources?

Biological Studies: Major Science Goals

- Study **integrated effects** of radiation/reduced-gravity/lunar-dust environment on biology at all levels over the **long term** (months)
  - especially related to human performance
- Establish **“transfer standards”** *via* correlated experiments at molecular, cellular, and whole-organism levels
  - transfer standards correlate the output from biosentinel (microorganisms, cells) measurements with responses of higher organisms (rodents, humans)
  - this enables future robotic biosentinel planetary missions to more accurately predict consequences to humans
  - key studies:
    - DNA damage
    - cell membrane damage
    - oxidation effects
    - protein damage
- **Demonstrate & validate enabling bio-related technologies** to be used on future long-duration space/planetary missions
  - shielding - validate transport model results
  - human health and performance systems
  - countermeasure validation, optimization
  - environmental measurements - sensors, biosentinels
  - validate planetary protection strategies, technologies

Biological Studies: Critical Capabilities

- Autonomous integrated biological experimental systems
  - multiplexed gene, protein, metabolite measurements: bio pathways
  - cellular parameters: proliferation, damage repair, senescence, apoptosis
  - whole-organism effects: physiological indicators; biomarker levels; cognitive performance
  - little or no human attendance required
  - supported with power & telemetry for long durations (months)
- Crew participation
  - emplacement of autonomous systems: high-flux or regolith-shielded locations
  - human cognitive tests; physiological & biomarker samples for assay
  - retrieval, preservation of specimens for return (not all experiments)
  - animal experiments: food/water/waste module exchange
- Pre-mission development of complex autonomous biosystems
  - cellular/molecular/microorganism experiments (3 - 30 kg; days - months; 1 - 2 W/kg)
  - small animal (rodent) experiments (20 - 70 kg; days - weeks; 1.5 - 3 W/kg)

Lunar Biological Studies: Sortie vs Outpost Studies

- Sorties
  - Multiple sites: sample variable regolith properties
  - Robotic emplacement; autonomous long-term operation
  - (Optional) specimen retrieval/return on future sorties
  - Molecular/cellular/microorganism studies most amenable
  - Shielding model verification
  - Testbed for future outpost and long-duration missions
- Outpost: more sophisticated experiments that need crew participation
  - Rodents; humans (physiological; biomarkers; cognitive)
  - Correlate with molecular, cellular expts: develop transfer standards
  - Collect specimens, preserve/return
  - Validate complex systems
    - human health and performance
    - habitat strategies
    - planetary protection
    - life support systems
  - Testbed for future long-duration space/planetary missions

Biological Studies: Landing Site Criteria

- Choice of regolith type
  - Similar/identical to future outpost location
  - Multiple other locations to examine effects of regolith variability
- Continuous power availability, manageable thermal parameters
  - Permanently shadowed locations may be problematic
- Flux variations (minor consideration)
  - Natural features for regolith shielding strategy validation
  - Crater rims to maximize dose per unit time

Biological Studies: Synergism with Other Science Approaches

- Variability of regolith types important
  - Astrobiological studies also require numerous sites to study bombardment, history of the Sun
  - Geology, ISRU
- Continuous power, telemetry for long-term experiments
  - Geology
- For some bio experiments: low power, low mass, autonomous operation leaves more power, mass, and crew time for all other activities
- Crew attendance needed for certain experiment types, esp. at outpost
  - Geology, ISRU
- Robotic emplacement and/or specimen retrieval plays key role
  - Geology; ISRU; astronomy; preparation for outpost

Biological Studies: Feed-Forward to Mars

- Build Mars strategies upon results of studies of integrated effects of radiation, reduced gravity environment
  - Understand human performance consequences: cognition, immune system, wound healing, etc.
- Utilize transfer standards from long-term lunar bio-studies correlating responses of large organisms to molecular/cellular/microorganism responses
  - Subsequent biosentinel studies on robotic precursor missions to deep space and Mars can inform more accurately on aspects of the human risk
- Develop, validate countermeasures needed to assure human performance on Mars missions
  - Lunar outposts offer unique opportunities to validate countermeasures
  - Results from lunar studies will assist in new countermeasure development
- Demonstrate & validate enabling bio-related technologies for Mars missions
  - Shielding: validate transport model results; confirm bio-monitored shielding performance during solar proton events
  - human health and performance systems
  - environmental measurements - sensors, biosentinels
  - validate planetary protection strategies, technologies

Biological Studies: Open Issues

- Which particular effects of radiation, reduced gravity, or exposure to lunar dust are synergistic, which are antagonistic, which are simply additive?
- Do transport simulations, tissue-equivalent plastic models, and single-energy/single-particle-type terrestrial exposures accurately predict key features and effects (e.g. human performance) of biological radiation damage/repair in response to a complex spectrum of particle types and energies, particularly at solar proton events levels?
- Will development time and budget be sufficient to prepare sophisticated automated systems having less mass, needing less power, and requiring less human attendance?

Biological Studies: Contributions to Earth-Based Biomedicine

- Translational research: Lunar expedition discoveries and terrestrial biomedical advances interact bi-directionally
  - Lunar expedition bioresearch will be hypothesis-generating as well as hypothesis-testing
  - Terrestrial biomedical research, building on new hypotheses, discoveries and countermeasures, may lead to increased healthy-and-productive life spans on Earth
- Genomic damage: fundamental mechanisms and consequences are key common threads
- Lunar missions – mitigate modifications to biological processes caused by the integrated lunar environment, i.e. develop & prove countermeasures
  - Result: improved human performance
- Terrestrial impact – novel approaches to study & address earth-based pathogenesis and environmental health hazards
  - For example: new insights to minimize consequences of genomic damage from natural sources (solar UV // melanoma) or from medical procedures (radiation therapies // “collateral” cellular radiation damage)

Geology - Major Science Goals

- Measure bulk chemical composition of the Moon to constrain the processes by which elements were partitioned in the Earth-Moon system at the time of formation
- Sample early crustal rocks to understand the development of the magma ocean, formation of the crust and mantle, timing of anorthosite formation and other large intrusive magmatic events, size and composition of the lunar core
- Determine the ages, types and duration of volcanic activity, styles of eruption, duration of volcanism, and the spatial distribution of volcanic vents
- Determine the bombardment history of the lunar surface, and the variability and periodicity of impact flux through time
- Use the Moon's craters as a natural laboratory to study the large impact process, including the origin and mechanism of central peaks and basin ring development, excavation dynamics and dimensions, and the mechanics of ejecta emplacement
- Sample the complete regolith column in as many locations as possible to determine rates and processes of formation and modification over time

Geology: Critical Activities

- Investigating lunar geology will require EVA field work on the Moon by crew members, robotic adjuncts to this work for far-field remote sensing and sampling, and sample analysis both on the Moon and on Earth
- Sampling:
  - The full suite of lunar basalts to define the composition of the mantle
  - Pre-basin crustal units exposed in uplifted blocks around major impact basins (e.g., layers seen in Apennine Front at Silver Spur on Apollo 15)
  - As many specific large pre-Imbrian basin impact melt sheets as possible
  - Regolith layers found directly beneath datable rock units, such as basalt flows, achieved by use of drill cores, or by field work on rilles developed in lunar basalts (e.g., Schröters Valley at Aristarchus)
  - Stratigraphy and structure of remnant volcanic vents
  - Rocks of diverse ages for paleomagnetic measurements
- Measuring:
  - The thickness of the regolith blanket moon-wide
  - Gross scale lunar crustal composition by orbiting and landed spacecraft

Geology: Critical Capabilities

- **Length of stay on the lunar surface**
  - Probably no more than 20% of surface time will available for science (based on Apollo J-mission and ANSMET data)
  - Longer stay times equal more total crew time for science
- **The ability to do routine and frequent EVAs in all lunar environment extremes**
  - It is not possible to do geology effectively solely from the front seat of a pressurized rover or control seat of a teleoperator
  - Typical EVAs should be 8 hours long
- **Number of crewmembers simultaneously on EVA**
  - The more crew outside of the habitat, the greater the science return
- **Ability for crews to range away from lander or habitat site, over the horizon and beyond Apollo walk-back distance**
  - Exploration is about seeing what's over the next hill
  - The more ground we cover, the more rocks we see and sample, the farther afield we place geophysical instruments, the more science return we achieve
  - Distances in unpressurized rovers should be well in excess of 10 km
  - Pressurized rovers should be able to roam up to 100 km from an outpost site
  - Long-distance traverses can be supplemented by telerobotic exploration

Geology: Critical Capabilities

- **The ability to conduct planet-wide robotic reconnaissance**
  - We need to be able to sample materials from the whole Moon
  - Teleoperation from outpost and Earth
- **Ability to see into the lunar sub-surface**
  - We need to add a 3rd dimension to surface data, through deep drilling, regolith trenching, radial sampling of crater ejecta, and traversing large crater walls
  - Deeper is better, but difficulty increases non-linearly (more likely exponentially)
  - Rough depth targets: 3 m on sortie missions (similar to Apollo J-missions); increase to drilling ≈10 m (base of regolith) early in outpost mission; trenching the whole regolith column later in the outpost phase
- **Access to geochemical analysis tools on the lunar surface**
  - Initial analysis of samples guides continuing field work and permits more thorough discovery possibilities
  - Initial analysis also reduces returned sample mass

Geology: Sortie vs. Outpost Studies

- **Sorties**:
  - Allows human investigation of more than one site
    - Site visit duration is short
    - Reconnaissance geology and sampling only level possible
  - Can benefit from robotic operation before crew arrival to do basic remote sensing site reconnaissance and teleoperation of robots after crew departure
  - Possibility of doing Apollo-style investigation on sites other than outpost
    - Increases the number of sites we have direct information from (as opposed to orbital remotely sensed data)
- **Outpost**
  - Committed to a single site for a long period of time
  - Ability to spend more time on a single area, expand beyond the sites visited on a reconnaissance mission and investigate geologic problems in depth
  - More synergism between geological and geophysical studies
  - Opportunity for physical sampling (e.g., drilling) to test conclusions from geophysical sounding of upper 100 meters

Geology: Landing Site Criteria

- **Geologic diversity:**
  - Outpost site should allow access to a variety of mare and highland terrains, preferably at the overlap of a variety of structural features and impact events (e.g, junction of Imbrium/Serenitatis Basin; Mare Ingenii and enclosing South Pole-Aitken Basin)
  - Later sortie missions may be targeted to interesting sites that have insufficient diversity to be candidates for outpost sites (e.g., Alphonsus dark halo craters; Marius Hills volcanic vents)
- **Compatibility with ISRU Site Selection Criteria:**
  - Early use of ISRU will enhance exploration capability and should provide easier access to lunar terrain
  - For two sites of equal science ranking, the site with the best ISRU potential should be the priority site

Geology: Synergism with Other Science Approaches

- Geology field work provides constraining data for interpreting geophysical data
- Extensive EVA provides data for human adaptation to fractional g during routine surface operations
  - Biology/human performance

Geology: Feed Forward to Mars

- Develop and test operational and scientific practices for use on Mars, including the routine and frequent EVAs, the use of pressurized rovers for long roves away from central outpost location and *in situ* sample analysis
- Develop the synergism of cooperative activity between human crews and telerobotic/autonomous robots
- Scientific results from lunar studies inform and direct planetary science investigations on other objects in the future (e.g., use of lunar stratigraphic time scale to calibrate planetary histories)

Geology: Open Issues

- **Crew training and preparation will need to change significantly from present ISS/Shuttle paradigm back to the Apollo approach**
  - Significant increase geologic “basic” training hours
  - Extensive field work to conduct training in real-world situations
  - For example, the Apollo 15 crew had 1000-1100 hours classroom and field training, including 16 different field trips
- **Site selection vs.. operational constraints**
  - As with Apollo, there will be significant tension between the need to go to interesting geologic locations and mission rules which may limit access to the most interesting terrains (e.g., Apollo constraints that prevented landing one J-mission in Copernicus to sample the central peak and crater floor)
- **What analytical tools should be available in the habitat and with EVA crewmembers?**
  - The ability to do a preliminary analysis of samples at the outpost site will inform our on-going operational planning
  - We need agreement on what capability should be available, so NASA can start to scope the mass/power/volume budgets for habitats and rovers

Geophysics: Major Science Goals

- Determine composition and structure of deep lunar interior to understand lunar bulk chemical composition and evolution
- Determine properties and stratigraphy of near surface (upper 100 meters) to understand regolith formation and nature of regolith-bedrock interface
- Determine mean heat flow and variability in heat flow to assess total radioactive element content (K, Th, U) of the Moon, hence unravel Moon’s composition and thermal history
- Determine the history of the lunar magnetic field

Geophysics: Critical Capabilities

- Seismometers for deep probing
  - As sensitive as those on Apollo
  - Broad band
  - Operation for at least 5 years
  - Enough to form a global network: carry on each sortie mission and to outpost
- Shallow surface studies
  - Need 1-meter vertical resolution and 10-meter horizontal resolution (or better)
  - Sounding of a statistically representative area, about 10x10 m
- Heat flow
  - Automated drilling to at least 5 meters
  - Astronaut installation of heat-flow probes
- Origin of lunar paleomagnetism
  - Detailed global characterization and distribution of magnetic anomalies
  - Study of lunar swirl deposits from orbit and surface
  - Collection of oriented, bedrock mare basalt samples
  - Collection of oriented, bedrock lunar crater and basin impact melt rocks

Geophysics: Sortie vs. Outpost Studies

- Sorties:
  - More than one site
  - Requires robotic operation after crew leaves (sounding, continuous power and data downloads from experiments)
  - Much of installation can be done robotically
- Outpost
  - More synergism between geological and geophysical studies
  - Opportunity for physical sampling (e.g., drilling) to test conclusions from geophysical sounding of upper 100 meters

Geophysics: Landing Site Criteria

- Deep seismic sounding:
  - Site antipodal to Apollo sites to use deep moonquakes (concentrated on nearside) to assess size of core
  - Stations spread out globally
- Heat flow:
  - Within Procellarum KREEP Terrain (PKT)
  - Far from PKT
  - Intermediate locations
- Shallow geophysical sounding:
  - Mare site to see regolith-basalt boundary and basalt-highland boundary
  - Highland to see regolith-megaregolith boundary and variations within upper part of megaregolith

Geophysics: Synergism with Other Science Approaches

- Continuous power to run long-lived experiments (seismometers, heat flow probes)
  - Also needed by biology
- Installation by humans (seismometers, heat flow probes)
  - Biology experiments?
  - Geology for study of subsurface
- Installation and survey by robotic systems (geophone lines, electro-magnetic sounding)
  - Geological exploration
  - Site surveying
    - ISRU
    - Astronomy
    - Civil engineering of outpost site

Geophysics: Feed Forward to Mars

- Develops and tests geophysical instrumentation for use on Mars
- Understand difficulties and advance use of telerobotic and autonomous robots to deploy geophysical instruments
- Develop appropriate power systems for long-lived geophysical stations
- Scientific synergy
  - lunar and martian paleomagnetism: brothers under the skin?

Geophysics: Open Issues

- Minimum number of seismic stations and distribution that are required to make a significant advance over our current knowledge of the deep interior
- Extent of human involvement in deploying geophysical instruments

Astrobiology: Major Science Goals

- Bombardment history of the Solar System
    - Determine timing of impact events in early history (> 3.5 Ga)
        - Assess reality of “late-heavy bombardment/terminal cataclysm”
        - Understand the composition of impactors, esp. as sources of volatiles
    - Quantify periodicity/episodicity of bombardment during later epochs (< 3.5 Ga)
    - Search for ancient Earth (or Venus or Mars) materials
- Solar history and stellar environment
    - Determine record of solar activity
        - Secular flux variation; flares
        - Changes in solar wind composition
    - Search for evidence of nearby supernovae and gamma ray burst events
    - Cosmic ray exposure history of Solar System
- Bio-organic contamination (organisms and molecules)
    - Quantify contributions from robotic exploration infrastructure
    - Quantify contributions from human exploration infrastructure
    - Test “life detection” technologies (assess potential for “false positives”)

Astrobiology: Critical Activities

- Collect samples from small number of major impact basins (early bombardment)
- Collect samples from diversity of smaller basins (esp. for later bombardment flux)
- Coring and trenching of regolith
- Petrographic and geochemical sample screening
- In situ bio-organic analyses

Astrobiology: Sortie vs Outpost Studies

- Sorties:
  - Purpose:
    - Sample major ancient basins (esp. South Pole-Aitken Basin)
    - Sample diversity of younger craters (the more the better; statistics key)
    - Sample buried regolith sites (e.g., Hadley Rille)
    - Assess bio-organic “environmental impact” of short duration exploration systems
  - Capabilities
    - Roving, sampling, telerobotic assistance, coring, screening, bio-organic analyses
    - Sample return to Earth
- Outpost
  - Purpose
    - Locus for screening of samples returned from diverse locations
    - Location for intensive subsurface study (drilling; trenching)
    - Assess bio-organic “environmental impact” of long duration exploration systems
  - Capabilities
    - As above but with greater global reach and/or denser regional coverage; more detailed screening; high volume sample return to outpost and to Earth

Astrobiology: Landing Site Prioritization

- Highest priority: Unambiguous sampling of a number of ancient basins (e.g., South Pole-Aitken)
- Secondary priority: Geographic diversity, global reach
- Tertiary priority: Proximal to buried paleoregoliths

Astrobiology: Synergism

- ISRU
  - Robust ISRU maximizes mass of sample that can be returned
  - Critical to facilitate global reach
- Geology
  - Critical capabilities are almost identical
  - Site criteria highly synergistic
- Geophysics
  - Site criteria are very synergistic
- Biology
  - Effects on contaminant organisms
  - Environmental impact of human life support technologies
- Astronomy
  - Radio astronomy experiments compatible with astrobiology site criteria

Astrobiology: Feed Forward to Mars

- Bombardment history relevant to understanding early Mars hence, to formulating future exploration goals
- Develop and test essential geological exploration infrastructure
- Develops and tests potential Mars ISRU technologies (e.g., excavation, soil handling, etc.)
- Develop and test potential life detection technologies
- Assesses environmental (bio-organic contamination) impact of exploration infrastructure and protocols

Astrobiology: Open Issues

- Which regions (other than South Pole-Aitken basin) and which specific landing sites are best prospects (i.e., an early bombardment landing site “short list”)?
- Will far side sorties be possible (and does SPA require this)?
- How definitively can late bombardment question be solved vs. # of sites visited?
- How much sample mass must be returned?
- How much sampling and return can be robotic?
- How diverse must sampling be to plausibly constrain post-3.5 billion year flux (a statistical question)?
- What level of analytical sophistication (e.g.,geochronology) is possible in situ with robots? During human sorties? In a lunar lab (Outpost)?
- Where are best prospects for trapped regolith?
- How practical is it to reach solar/stellar history science goals from regolith studies?
- Bio-organic analytical specifics

Astronomy: In Space and on the Moon

- The infrastructure to support human and robotic habitation on the Moon provides opportunities for advanced telescopes in space and on the Moon
  - Transportation allows for ready access to the lunar surface and to in-space locales such as Sun-Earth L2
- Lunar-based astronomy falls into two categories:
  - Unique opportunities provided by the lunar platform and gravity
  - Opportunistic: facilities on the Moon that take advantage of human presence for assembly and servicing

Astronomy: Potential and features of the Moon as an Observing Platform

- Extended stable platform for interferometry - valuable for fixed interferometer elements viewing along spin axis.
  - Free space the aperture synthesis can be in any direction, but always requires constant accurate station keeping and occasional repositioning
- Gravity, uniquely enabling for a liquid mirror telescope
- Slow sidereal rate
- As in free space:
  - Extreme cold available by sun-shielding < 50 K should be possible by a cylinder shield at poles
  - Near continuous solar power, near peaks of eternal light where observatory would be located
- Advantages over free space:
  - Very extended lifetime: no expendables required to maintain orbit indefinitely - free orbits such as L2 are not stable
  - Human and robotic infrastructure gives accessibility and sustained supporting infrastructure
- Astronomy area where moon has unique advantage:
  - Multi-wavelength, deep field astronomy: unique opportunity for investigating ultradeep field aligned along spin axis, with liquid mirrors and static long baseline interferometers
  - spinning mirror will cover 0.1 to 10 microns, set by 88K liquid. Interferometer will use use static dishes at 50K for longer wavelengths to 350 micron Alma limit

Deep field astronomy: Major Science Goals

- Direct observations of the first individual stars formed after the big bang, beyond range of JWST
- Extremely deep, high resolution study of a selected field
  - Focus of liquid mirror will be 2 - 10 microns where large mirror, focused survey from moon far more sensitive than JWST or proposed very large ground telescopes
- Images and spectra of highly redshifted stars and galaxies across the electromagnetic spectrum:
  - Liquid mirror 2-10 microns
  - Far IR interferometer 10-300 microns
  - boresighted x-ray telescope to spot high energy variables in the field.
- First stars in the universe ($z=20$, with fluxes in Ly-α and He1620A of about 100 pJy) will be detectable
- Study the detailed near infrared structure in nearby galaxies
- Lunar deep survey telescopes ideal for generation beyond JWST, with much higher sensitivity and resolution with huge, gravity-enabled, mirrors.

Deep field astronomy: A unique capability from the moon

- Survey made of fixed region of space along moon's spin axis
- Telescopes and arrays don't require steering, remain boresighted for ultradeep survey along axis
- Range of static, boresighted telescopes and interferometers to span the breadth of the electromagnetic spectrum, for deepest understanding
- Primary candidate survey telescopes are:
  - Single large spinning liquid mirror telescope for optical/infrared
  - Multiple static mirrors for interferometer in the 10-300 micron region inacessible to Alma.
- North pole may be preferred over south, where view includes many stars in Large Magellanic Cloud
-

Deep field astronomy: spinning liquid mirror telescope

- Extremely large spin axis telescope takes advantage of gravity, unique to moon
- Primary mirror made from spinning liquid in dished container
  - Ground telescope operational with 6 m spinning mercury mirror
  - 1 m liquid flat being tested to optical diffraction limit at U Az
  - Dish with liquid on cryo bearing demonstrated in NIAC model
- Telescope located at pole to point along spin axis
- Apertures up to 100 m in diameter feasible this way
- Tolerance on dish accuracy relaxed by factor >1000 compared to free space. Gravity acting on liquid yields the high accuracy automatically.
- Polar location favored also for key infrared spectral region to see high redshift objects
  - Telescope radiatively cooled with cylindrical solar radiation shield
  - Cooling allows use of superconducting bearing for spinning dish

Deep field astronomy: long baseline interferometers

- Moon offers unique stable platform for arrays up to many km baseline
- Dish elements fixed pole-pointed - moon’s rotation gives aperture synthesis
- Wide survey field along spin axis field requires only simple fixed combining optics
- Target is the same ultradeep annular field 1.55 degrees radius about ecliptic pole seen by liquid mirror (set by moon’s 18 year precession)
- Unique deep imaging and high resolution
- Compared to free-flyer interferometers
  - No need for continuous tracking and precision station keeping or expendables
  - Human or robotic servicing over long temporal baseline
- Highest resolution for long spatial baseline UV-optical-IR wavelengths
  - ≥ 10 kilometer baseline

Deep field astronomy: Sortie v. Outpost Studies

- Sorties:
  - Need to determine if polar sites have a dust problem – possible high altitude scattering layer from electrostatically levitated dust
  - Robotic lander could perform site survey mission – or it could be placed as a sortie instrument at the pole – desirable to be at exact site of the observatory – at least one year operation
  - Prototype 2 m liquid mirror telescope is an ideal sortie mission
- Outpost
  - Large (> 20 m) liquid mirror telescope could be constructed and maintained from the outpost
  - Relative contribution of teleoperated robotics v. direct human interaction needs to be studied

Deep field astronomy: Landing Site Criteria

- Liquid mirror telescopes:
  - Polar sites essential
- Interferometer/other telescopes:
  - Polar sites desirable from heat management perspective and synergy of boresight with liquid mirror
  - IR instruments must be cooled to below 80K – polar location with a sun shield or location in permanently shadowed crater
  - Intermediate locations
  - Relatively flat terrain desirable but not essential for polar axis boresighted interferometer; may be difficult to obtain without significant site preparation

Deep field astronomy: Synergism with Other Science Approaches

- Continuous power to run long-term experiments – especially thermal management
- Moderately high rate data transfer needed (100’s MBPS)
- Interplay with large industrial processing
- Must be sufficiently far from dust and vibration-producing activities such as ISRU and human activities
- May be merit in designating one pole as a “reserve” for minimum impact experiments such as astronomy
  - Could be a useful site for other delicate experiments such as future gravity wave or other physics experiments

Deep field astronomy: Feed Forward to Mars

- Operational experience in building, emplacing, and maintaining large service facilities on planetary surfaces

Deep field astronomy: Open Issues

- Technology investment required to assess and advance readiness level
- Once technical feasibility and performance better understood, relevance of ultra-deep field science goals to NASA and national priorities via NRC review with community input
- Cost of large lunar instruments must trade favorably with free-flyer alternatives and be justified by unique science return
- Environment issues must be assessed in depth: dust, thermal environment, surface conditions (smoothness), etc.
- Extent of human and robotic involvement in deploying and operating astrophysical instruments
- Degree of isolation from other activities such as ISRU and human outpost must be determined
- May need a special reservation – the north pole?

Low frequency Radio Astronomy : Major Science Goals

- Opening up a new astronomical window at frequencies below ~10 MHz, which are opaque from the surface of the Earth, a very low frequency array can be used to:
  - Directly detect hydrogen just after the big bang;
  - Detect low frequency bursts from Extrasolar Giant Planets of sub-Jovian size, as well as from the larger EGPs;
  - Perform ultra high-energy particle physics (neutrinos and cosmic rays).

Low frequency Radio Astronomy: Critical Capabilities

- Low Frequency Array with significant collecting area required:
  - potentially need as many as 10000 element array
  - however, each element is a simple dipole
  - start much smaller, array grows over time
- Location of VLF facilities must be on lunar far side to shield from terrestrial radio noise
  - Operation during lunar night to similarly eliminate solar noise

Low frequency Radio Astronomy: Sortie vs. Outpost Studies

- Sorties:
  - Characterize Earth-based Radio Frequency Interference (RFI), along with temporal variation
  - Measure density and temporal variation of lunar ionosphere
  - Characterize reflectivity of lunar surface
  - Characterize thermal environment
  - Characterize seismic environment
  - All should be done at various locations
  - First two above require robotic operation after crew leaves (sounding, continuous power and data downloads from experiments)
  - Much of installation can be done robotically
- Outpost
  - Permanent outpost not needed for final array, but major initial effort to construct/install - especially the correlator
  - Telerobotic vs.. human installation must be studied

Low frequency Radio Astronomy: Landing Site Criteria

- Must be on far side, probably > 30 deg from limb, to protect from Earth-based RFI
  - Exact minimum required separation from near side needs study, possibly experiments
  - Moon is set aside as a radio quiet zone (Article 22, Section V of the ITU Radio Regulations), this should be recognized and respected in all lunar activities
- Should be near-equatorial, to see most of the sky
- Need multiple flat areas eventually, but one to begin with. Floor of Tsiolkovsky, Mare Ingenii are possible candidate sites

Low frequency Radio Astronomy: Synergism with Other Science Approaches

- Continuous power to run the array for long periods, unattended.
- Moderately high rate data transfer needed (100s MB/s)
- For sorties, need to characterize thermal and seismic properties of candidate locations
- Use ISRU to make radio antenna elements?

Low frequency Radio Astronomy: Feed Forward to Mars

- Interferometry using long baseline between Mars-bound spacecraft and the Moon

Low frequency Radio Astronomy: Open Issues

- Extent and effect of lunar ionosphere
- RFI levels (modeled, but needs direct measurement)
- Effect of reflections off of the lunar surface (is a ground screen needed for the dipoles?)
- Extent of human involvement in deploying dipoles and electronics (notably the correlator)
- Make antenna elements on Moon? (role of ISRU)

Observing Earth and Environs from the Moon

- Continuous, stable view of Earth from front side locations
  - Earth maintains constant sky position with only very slow wobble
- Wide field; global + cislunar space
- Concurrent global observations in many wavelengths
- Unique observations enabled (e.g., whole magnetosphere)
- Lunar resources and infrastructure to build observatories and add capability
- Access to facilities by humans ensures long lifetime, maintenance, servicing, upgrading

Observing Earth and Environs: Major Science Goals

- Observe climate change on Earth
  - Synoptic view of Earth’s surface and atmosphere
- Observing and Measuring Hypothesized Climate Change Drivers
  - Terrestrially-produced atmospheric gasses, solar variability and/or galactic cosmic ray-induced changes can be evaluated and tested using synoptic global views of Earth from the Moon
- Cislunar Space Awareness and Support
  - Information to track controlled and uncontrolled objects in the Earth-Moon system
- Whole Magnetosphere Imaging
  - From Moon, Earth’s magnetosphere is continuously visible
  - Wide-angle coverage, temporal variations

Observing Earth and Environs: Critical Capabilities

- Synchronous viewing cross the electromagnetic spectrum
- Stable seismic environment
- Vast distributed aperture instruments across the Moon and coordinated with instruments on Earth
- Common "on board" (lunar) data processing, management, servicing, repairs and updating of facilities

Observing Earth and Environs: Landing Site Criteria

- Diverse locations, depending on specific measurements: On the poles of the Moon and other key locations on the front, back and rim of the Moon
- Assurance of Observations/Survivability: strategic locations on the Moon may enable survival of assets, except for cataclysmic cosmic events.

Observing Earth and Environs: Open Issues

- Study trade offs among potential locations:
  - Earth-orbiting
  - Earth-Moon L2
  - On the lunar surface
- Trade off considerations:
  - Spatial resolution
  - Value of synoptic view
  - Cost of installation
  - Lifetime
  - Servicing needs and costs
  - Synergism with other facilities such as astronomical observatories

Qualitative Assessment of User Needs

User Needs-1

- Yes: Capability needed
- No: Capability not needed
- Qualitative Assessments:
  - High: Need for high level of activity, power, facility space, time
  - **Medium:** Need for intermediate level of activity, etc.
  - Low: Need for little activity; in some case none (not identified as most activities require some resources)
- Categorized by critical surface activity
  - ISRU Processing (acquisition of regolith, phase separation if needed, chemical processing, resource production)
  - Observations of regolith trenches (requires human field work, aided by robotic techniques)

User Needs-2

- Categorized by critical surface activity (continued)
  - ISRU product observations (inspection of product to monitor effectiveness)
  - Instrument operations (servicing of instruments deployed on the surface, retrieval of samples if necessary; includes biological, geophysical, atmospheric, and other instruments)
  - Deploy instruments (all types: biological, geophysical, atmospheric, others)
  - Geological field studies
  - Industrial experiments (experiment set up and repair, monitor products of experiments)
  - Teleoperation experiments (mostly for geologic field work, but for some other tasks such as ISRU product observations, equipment inspection and repair)

User Needs-3

Capability	**ISRU Processing**	**Observations of Regolith Trenches**	**ISRU Product Observations**	**Instrument Operations**	**Deploy Instruments**	**Geological Field Studies**	**Industrial Experiments**	**Teleoperation Experiments**
Crew time for science								
EVA	Low	Medium	Low	Low	Medium	High	Low	Low
IVA	Low	Low	Low	Low	Low	Low	Medium	Low
Teleoperation								
Humans--Moon	Low	Low	Low	Low	Low	Low	Low	Medium
Humans--Earth	Low	Low	Medium	Low	Low	High	Low	High
Volume in pressurized habitat								Low
Laboratory	Low	Medium	Medium	Low	Low	Medium	Medium	
Control station	Low	Low	Low	Low	Low	Low	Low	Medium
Repair	Medium	Low	Low	Medium	Medium	Low	Low	Medium
Location								
Near outpost	High	High	High	High	High	High	High	High
Remote (>25 km)	Low	Low	Low	High	Low	Medium	Low	Low

User Needs-4

Capability	**ISRU Processing**	**Observations of Regolith Trenches**	**ISRU Product Observations**	**Instrument Operations**	**Deploy Instruments**	**Geological Field Studies**	**Industrial Experiments**	**Teleoperation Experiments**
Power								
Continuous	**Yes**		**Yes**	**Yes**	**N/A**		**Yes**	
Intermittent		**Yes**			**N/A**	**Yes**		**Yes**
Outpost grid	**Yes**	**Yes**	**Yes**	**Yes**	**N/A**		**Yes**	**Yes (contl)**
Stand-alone				**Yes**	**N/A**	**Yes**		**Yes (field)**
Communications								
Data	**High**	**Medium**	**High**	**Medium**	**Low**	**Medium**	**Medium**	**High**
Audio	**Low**	**High**	**Low**	**Low**	**Medium**	**High**	**Low**	**Low**
Video	**Medium**	**High**	**Medium**	**Low**	**Medium**	**High**	**Low**	**High**
Navigation positional accuracy	**Low**	**Low**	**Low**	**Low**	**Low**	**High**	**Low**	**High**

User Needs-5

Capability	**ISRU Processing**	**Observations of Regolith Trenches**	**ISRU Product Observations**	**Instrument Operations**	**Deploy Instruments**	**Geological Field Studies**	**Industrial Experiments**	**Teleoperation Experiments**
Returned Samples	**Yes**	**Yes**	**Yes**	**No**	**No**	**Yes**	**Yes**	**No**
Accurate curation	**Yes**	**Yes**	**Yes**			**Yes**	**Yes**	
Sealed containers	**Yes**	**Yes**	**Yes**			**Yes**	**Yes**	
Temp. preservation	**No**	**No**	**No**			**No**	**No**	