



NEXT STEPS ON THE MOON

REPORT OF THE SPECIFIC ACTION TEAM

Specific Action Team Charter

- SAT commissioned by Science Mission Directorate, Planetary Science Division
 - Assess lunar missions needed to address new lunar science questions revealed by progress in lunar sample studies as well as results from recent lunar missions (including LADEE, GRAIL, and the on-going Lunar Reconnaissance Orbiter) mission
 - Determine desirable precursor instruments and/or missions to enhance human exploration and address Strategic Knowledge Gaps
 - Determine on-ramps for potential commercial involvement
 - Consider science activity enhancements offered by human presence on the lunar surface
 - Activities or new modes of operation that could be employed by existing lunar assets (e.g., ARTEMIS or LRO) to facilitate future discoveries or surface activities
 - Identify potential technology developments that would enhance lunar and Solar System science

NEXT-SAT Membership

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NEXT-SAT Assumptions

- SAT focused on robotic options, but there was unanimous agreement that human exploration of the Moon has significant science value and would dramatically enhance all proposed lunar surface exploration activities
- **Emphasis was placed on missions that could be feasibly carried out during the next 5 years**
 - NEXT-SAT developed notional mission example archetypes representing science investigations that would impact solar system science, advance exploration goals, and answer key lunar geology questions
 - No priority was assessed amongst mission archetypes
- The SAT did not attempt to do high-fidelity cost estimation for uncrewed missions
 - **We encourage NASA to carry out concept studies of missions highlighted by NEXT-SAT to form a complete basis for future decision-making**

NEXT-SAT Primary Finding

- **FINDING:** Lunar science presently has a well-developed slate of compelling science questions that are profoundly impactful for understanding the entire Solar System. There are numerous options for lunar missions to address these questions that would provide openings to make dramatic, paradigm-shifting advances in planetary science
 - Absolute ages of lunar geologic units
 - Understanding lunar volatile content, form, and distribution
 - Understanding the structure of the lunar interior
 - Characterizing the formation of magnetic anomalies
 - Understanding planetary volcanic processes: styles, histories, locations
 - Understanding the time-stratigraphy of basin-forming impacts
 - Understanding the Moon's resource potential
- These questions can be addressed through a combination of dedicated science missions or hosted payloads
 - Sample return missions (cross-cut numerous themes)
 - Rovers (e.g., mobility required)
 - Stationary landers

NEXT-SAT Finding: Commercial Opportunities

- **FINDING:** NEXT-SAT references the Finding 3 arising from the 2017 LEAG Commercial Advisory Board meeting. Commercial entities should be employed to the fullest practical extent to increase competition, decrease costs, and increase the flight rate.
 - “In addition to paying for payload flights, NASA should strongly consider buying transportation services, samples, and/or data. In order for this to succeed, the nature of the samples/data required must be adequately specified.”
- **FINDING:** There are numerous potential opportunities for commercial services, with NASA as a customer, to play a role in lunar surface exploration. Commercial opportunities include, but are not limited to:
 - Providing communications relay services to enable far side and polar missions
 - Commercial surface delivery services
 - Dedicated sample return missions
 - Rover recharging base station providing communications, power, and other utilities to surface assets

NEXT-SAT Finding: Use of Existing Missions

- **FINDING:** LRO observations of the Chang'e-3 mission activities on the surface pointed to the kinds of science and operational support that LRO data can enable and support for future missions
 - Future mission teams should leverage active targeting from LRO instruments to ensure that data for site selection certification is readily available, and interface with the LRO project team to enable comprehensive mission support and new science

Example Missions and Investigations Addressing Key Science Questions

- Orbital Missions
 - Global compositional information
 - Next-generation hyperspectral imaging system with higher spatial resolution than Kaguya, Chandrayaan-1, and LRO instruments
 - Global Major-minor element maps
 - XRF Spectrometer
 - Polar hydrogen/volatile maps
 - Bi-static radar
 - Laser frost-finder
 - Impactors
 - Reveal details about subsurface
 - More LCROSS-style missions
 - Relay satellites/navigational aids

Example Missions and Investigations Addressing Key Science Questions

- Fixed, Stationary Landers
 - Polar region landed mission
 - Understand plasma and electrical environment of lunar poles
 - Lunar Geophysical Network
 - Understand the lunar interior at 3+ locations across lunar surface
- Mobility-desired missions (rovers, hoppers)
 - Understand origin of magnetic anomalies - rover traverse across a lunar magnetic anomaly
 - Understand volcanic processes - rover traverse through complex terrain (Marius Hills volcanic complex, Hadley Rille), absolute ages and geochemistry of silicic volcanoes (Lassell Massif, Gruithuisen Domes)
 - Understand resource potential of lunar poles - rover traverse through several permanently shadowed regions
 - Understand the resource potential and geology of lunar pyroclastic deposits - Bulk chemistry, geochemistry, and depth of the
 - Understand history of lunar volcanism - absolute ages of proposed young basalt units,
 - Understand lunar tectonic processes - rover traverse over a local thrust fault
 - Understand geology of lunar lava tubes - land and explore sublunarean voids
 - Understand the time-stratigraphy of lunar basin formation - determine absolute ages of key impact melt deposits

Example Missions Addressing Key Science Questions

- CubeSat/Smallsat
 - Characteristics of magnetic anomalies
 - Orbital mapping of polar volatile deposits
- Sample Return Missions
 - Numerous proposed targets for sample return missions across the entire lunar surface, e.g.
 - Silicic volcanic materials (lunar differentiation)
 - Erastoshenian and Copernican mare basalts (lunar volcanism)
 - Ancient Buried Mare Basalts (lunar volcanism)
 - Polar volatile deposits
 - Regional Pyroclastic deposits
 -and dozens more!

Technology Investments to Spur Exploration

- **FINDING:** Despite clear community interest and compelling science questions, technology development for lunar missions has languished. Specific investments in key technologies (both instrumentation and aspects of spacecraft engineering) are needed to spur a credible lunar exploration program. Such investments could be part of focused mission development activities. Increasing flight rates leveraging commercial opportunities would provides flight opportunities for new instruments.
 - Technologies to enable safe landing - hazard avoidance and terrain navigation
 - Technologies to enable spacecraft to survive a lunar night multiple times
 - Example: Lunar geophysical network requires extended surface operations
 - Reusable sample return vehicles
 - Lunar mobility systems - capability to traverse relatively steep slopes and boulder fields found near large, scientifically valuable lunar craters
 - Instrument investment examples:
 - Geophysical instruments
 - Mass spectrometers for trace element analysis
 - In-situ age dating

Missions Needed to Investigate Lunar Science Questions

- NEXT-SAT determined key science questions and engineering questions required to address key science questions arising from recent mission and lunar sample investigations, guided by preliminary outcomes from the Advancing Science of the Moon Special Action Team.
- For each science question, NEXT-SAT determined measurements and mission goals and payloads for five different types of missions on the following slides:
 - Orbiters
 - Smallsats (40kg to the surface),
 - Landers and Rovers > 40 kg to surface
 - Sample Return missions

Understanding Irregular Mare Patches: Texture, composition, age, volume, emplacement mechanism

- Orbiters: High spectral-spatial resolution for spectroscopy/mineralogy with resolution sufficient to resolve the features smaller than those discerned using the highest-resolution LROC NAC images.
- Up to 40 kg payload to the lunar surface. No night survival: descent imaging, major element chemistry, macroscale imaging, microscopic imaging; possible potential application for emerging in-situ geochronology techniques, depending on payload mass.
- >40-500 kg payload lander, mobility, night survival: in situ geochronology, plus payload above, in-depth exploration at several exploration study areas within a single site of proposed Copernican volcanism.
- Sample Return. Examine source regions, multi-system geochronology, detailed major and trace element geochemistry. Static lander to return regolith sample. Sampling device on rover could get samples from multiple locations.
- Desired Technology Investments: precision landing and hazard avoidance. In situ geochronology. Rover development. Sample handling.

Lunar Magnetic Anomalies

Orbiters: Low passes with magnetometer-equipped spacecraft. Obtain contours and lateral topology of magnetic fields near, but not at, the surface

Up to 40 kg payload to the lunar surface. No night survival: In-situ measurements of surface magnetic fields; measurement of radiation environment of swirls to understand solar wind interactions with surface

>40-500 kg payload lander, mobility, night survival: Traverse around a swirl, measure the magnetic field intensity and interactions with surface and implications for radiation environment

Sample Return. Return regolith samples from a swirl in order to measure the composition, absolute ages, magnetic properties, and physical characteristics of the regolith within that swirl

Desired technology investments: Precision landing and hazard avoidance; rover development; sample handling.

Understand the Structure of the Lunar Interior

- **Orbiters**: Lagrange orbit enables laser interferometry to monitor for seismically-induced surface changes (post-seismic deformation) and/or fault activation. Impact flash monitoring as “active source” for surface-deployed seismic instruments (esp. farside).
- **Up to 40 kg payload to the lunar surface. No night survival**: Small-aperture local seismic array for regional crustal structure determination using active source, passive seismic, passive retroreflectors for laser ranging; heat flow probes
- **>40-500 kg payload lander, mobility, night survival**: Multi-node geophysical observatory consisting of a broadband seismometer, heat flow probe, laser retroreflector, and EM sounding experiment (magnetometer, electrometer, langmuir probe) for global internal structure and thermal determination.
- **Sample Return**: Sample return of a mantle xenolith in order to determine the composition of the lunar mantle.
- **Desired Technology Investments**: Heat-probe deployment mechanisms, thermal shielding, long-lived power sources enabling 5-10 year survival

Polar Volatiles: Composition, Physical State, Form, Distribution, and Context

- Orbiters: Surface mineralogy/ice mapping (Lunar Flashlight, Lunar IceCube, KPLO ShadowCam), improved resolution hydrogen mapping (LunaH-Map). High resolution SAR.
- Up to 40 kg payload to the lunar surface. No mobility, no night survival: Image surface within PSR, identify surficial ice composition, obtain subsurface sample and determine volatile abundance, chemistry, isotopics. Stratigraphy if possible. (Many landing sites needed for lateral coverage.)
- >40-500 kg payload lander, mobility, night and out-of-comm survival: chemical & isotopic composition, physical state, lateral/vertical distribution via subsurface sample analysis from at least 1 meter depth at multiple stations. Measure subsurface H concentration continuously.
- Sample Return. Return of volatile-bearing materials in pristine condition from multiple polar locations.
- Desired Technology Investments: Precision landing and hazard avoidance. Cryogenic sample materials handling, lossless storage. Rover development, including thermal management in cryogenic environment.

Bombardment History of the Inner Solar System

- Orbiters: Long-duration global flash monitoring from orbit, particularly to gauge the current farside impact rate.
- Up to 40 kg payload to the lunar surface. No mobility, no night survival: Exploration of large exposures of impact basin melt materials (e.g., Nectaris, Crisium) involving descent imaging, surface operations imaging, major element chemistry, imaging, possible potential application for emerging in-situ geochronology techniques, depending on payload mass.
- >40-500 kg payload lander, mobility, night and out-of-comm survival: in situ geochronology, plus payload above, in-depth exploration at several exploration study areas involving exposures of impact melt deposits thought to originate from large basin-forming impact.
- Sample Return. Return of impact melt materials from major basin-forming impacts (SPA, Nectaris, Crisium).
- **Desired Technology Investments**: Precision landing and hazard avoidance.