The International Lunar Network (ILN) is an initiative of 9 national space agencies to establish a set of robotic geophysical monitoring stations on the surface of the Moon.

The ILN accomplishes high priority science by coordinating landed stations (nodes) from multiple space agencies.

ILN nodes will fly a core set of instruments, plus additional passive, active, ISRU, or engineering experiments, as desired by each space agency.

Contributions could include orbiter support, tracking, communications, and closely related science.

To guide the ILN initiative, a non-binding “Statement of Intent” was signed on July 24, 2008, by Canada, France, Germany, India, Italy, Japan, Korea, the UK, and the U.S.

Working Groups established for Core Instrumentation (WG1), Communications (WG2), Site Selection (WG3), and Enabling Technologies (WG4)

White paper completed by WG2; white papers near complete for WG1 & WG4

Site Selection working group not yet seated

The U.S. contribution to ILN is the Anchor Nodes Project

NASA has been conducting an Anchor Nodes Science Definition Team and Engineering Pre-Phase A Study

Two mission concepts were developed by MSFC/APL based on SMD direction:

- **ASO Mission Concept**
  - **Cost Estimate:** $836M
  - **Generator-Advanced Radioisotope Generator (ASRG)**
  - **Launch:** Atlas V 401
  - **Payload:** 115/115 W

- **ASOG Mission Concept**
  - **Cost Estimate:** $650M
  - **Wet mass (cruise/lander):** 798260 kg
  - **Power - cruise:** 95 W

Independent PA&E Technical, Cost, & Schedule Review is complete:

- "Project's costs & schedule estimates are reasonable for the mission concepts developed."
- Decadal class lunar network science is a New Frontiers cost class of mission.

Lunar Quest budget for Anchor Nodes / Future Missions ($240M through FY2014) is insufficient to achieve the ILN SDT science objectives
A Geophysical Network is recommended in the Planetary Decadal Survey (2003), the Scientific Context for the Exploration of the Moon (2007), the NAC Workshop on Enabling Science in the Lunar Architecture (2007), and Opening New Frontiers in Space (2008) to include, at a minimum, seismic and heat flow sensors, and new laser ranging retroreflectors. Coordinated with those of other countries that are missions in their space exploration strategies.ded sites should be four, more or less at least one farside site (no retroflector.

Pre-Phase A Cost Estimates for U.S. Anchor Nodes have been validated through independent PA&E technical, schedule and cost review:
- Cost estimates of mission concepts and instruments are in-family with historic NASA planetary missions
- Cost analysis is traceable and contains supporting documentation and technical data
- Due to the high cost of a Decadal class Anchor Nodes mission, lunar network science has been remanded to the Decadal Survey for prioritization
- Robotic Lunar Lander team is proceeding with risk reduction and technology development of the small lunar lander design
- Lander designs are capable of supporting the selected SMD science mission based on results from Decadal Survey.

International Lunar Network Science
Barbara Cohen, ILN Project Scientist

Outline

Scientific motivation
Science Definition Team
- Formulation and prioritization of science and measurement goals
- Science baseline and floor definitions
Science mission drivers
- Number of Nodes
- Day/Night Operations
- Lifetime
- Landing sites
- Instrument payload
- Launch data

Scientific Motivation

The Moon uniquely preserves a record of geologic processes of early planetary evolution
- The Moon is a terrestrial body – it formed and evolved in a similar manner to Earth, Mars, Mercury, Venus, and large asteroids
- The Moon is a differentiated body, with a layered internal structure (crust, mantle, and core)
- The Moon is an active body, experiencing thousands of deep moonquakes each year, releasing primordial heat, conducting electricity, and wobbling in its orbit

The goal of a Lunar Geophysical Network is to understand the interior structure and composition of the moon.

Genesis of the Geophysical Network


Lunar Interior Structure: The Theory

- Mars-sized body slammed into the proto-Earth at 4.56 Ga
- Moon formed out of hot crust/upper mantle component - lack of metal & volatiles
- Moon and Earth differentiated via igneous processes
- Basaltic oceanic via mantle density overturn
- Incompatible elements in KREEP layer
- Redistribution by impact processes
• The complete Apollo seismic network (4 nodes) operated from April 22, 1972 to Sept. 30 1977. Penetrated ~800 km deep.

• Crust on near side is 30-40 km thick; far side is thicker (60 km). It has an anorthositic composition; lateral variations exist.

• Geochemical arguments hypothesize that the lunar mantle is layered and of a different composition than Earth's mantle.

• Magmatism was most active > 3 Ga, therefore heat flow in the mantle was higher then.

• There is probably a small (250-350 km diameter) core.

• There are many unresolved science questions about the interior of the Moon, its evolution, and implications for other planets.
  - Lunar Core
  - What are the vertical structural and compositional gradients?
  - What are the mechanics, depth, and age of the largest seismic events?
  - What is the climatic state of the lunar core?

• The next generation of geophysical measurements is intended to directly detect a planetary core, to provide a framework for interior models, and to understand changes within a planet. These objectives will substantially improve upon our current knowledge of planetary interiors.

• NASA HQ convened an independent Science Definition Team to address the science uniquely enabled by a network, March 2008.
  - "The clear focus of the SDT is to address what science is uniquely enabled by the synergy of a network, within the context provided by previous community based activities."
  - Define and prioritize the scientific objectives for the ILN.
  - Define measurements required to address the scientific objectives.
  - Define instrumentation required to address these measurements.
  - Define criteria for selection of the initial two sites.
  - Identify technical challenges.
  - To the extent that there is still remaining mass and power available for an additional instrument, a priority list of what measurements that instrument should provide.

• Findings and recommendations reported to the Planetary Science Division Director and SMD AA July 2008; final report January 2009.

• Science Definition Team: Joe Veverka, Barbara Cohen, Bruce Banerdt, Andrew Dombard, Lindy Elkins-Tanton, Bob Grimm, Yosio Nakamura, Clive Neal, Jeff Plescia, Sue Smrekar, Ben Weiss.

• Defined ILN science objectives => derived mission objectives => measurement and mission requirements.

• The goal of a Lunar Geophysical Network is to understand the interior structure and composition of the moon:
  - Seismometry
  - Heat flow
  - Electromagnetic sounding
  - Laser ranging

• The next generation of geophysical measurements have to improve on our current (largely Apollo-derived) knowledge:
  - wider geographical placement
  - more sensitive instrumentation
  - longer baselines of observation

• Geophysical Network Science Baseline Mission
  - Four stations, four instruments, concurrently active, lifetime of 6 years; tenside coverage desirable, or nearside stations within ~20° of the limb.

• Science Floor Mission
  - Two stations, seismometer only, concurrently active, lifetime of 2+ years, stations placed relative to A33 moonquake nest hypocenter.

• SDT defined graceful descopes between Baseline and Science Floor.
  - Instrument requirements, number and type of instruments, total lifetime, reduced power modes for nighttime operations, number of nodes.
  - "Two nodes are insufficient for achieving major new lunar science. Therefore, the SDT strongly advocates a Network Science Baseline Mission, where two initial nodes are joined with at least two additional nodes to form a larger network for a combined 6-year minimum operational lifetime." SDT report p. 2.

  "NASA must continue its long-term partnership with the international community for the success of the entire International Lunar Network." SDT report p. 33.
Find the speed of seismic waves through the Moon – related to the material it is made of.

- Need to simultaneously measure 4 independent pieces of information:
  - Use three stations to triangulate the location of the moonquake
  - Measure time for waves to reach a 4th sensor at a known distance
- Calculate the mean speed of waves
- The more independent stations, the more lateral variability can be investigated
- All four stations must be simultaneously and continuously operational (day and night)

Need to observe multiple seismic events
- Apollo gave us statistical information about frequency and cyclicity
- For network science baseline, need to capture information over a lunar tidal cycle (6 years) – longer baseline than Apollo, provides ~6 strong, shallow moonquakes
- For science floor (2 nodes), limited science objectives can be accomplished from deep moonquakes in a shorter time (2 years).
- Other experiments need two years or less – not drivers.

Launch Date
- Strong desire for farside placement, but if necessary, nearside sites may exist
- Two nodes at poles is below the science floor
  - If four nodes placed simultaneously, two might be polar, but third and fourth nodes have to be nonpolar, so lander design can’t be exclusively polar
  - International partners may well end up at a pole for their own exploration
- Synthetic seismogram study will evaluate potential locations
- Site selection should be done with full community input, plus constraints from engineering

Notional Payloads
- **Seismometry**
  - Instrument: Balvanera
  - Mass: 5 kg
  - Data rate: 100 GB/year
  - Power: 36 W
  - Assumed: Estimated
- **NRCI**
  - Instrument: NEA
  - Mass: 1.5 kg
  - Data rate: 10 GB/year
  - Power: 2.2 W
  - Assumed: Estimated
- **EM Sensing**
  - Instrument: Magnetometer, longhorn probe
  - Mass: 2.8 kg
  - Data rate: 20 GB/year
  - Power: 47 W
  - Assumed: Estimated
- **Laser Ranging**
  - Instrument: Laser interferometer
  - Mass: 0.9 kg
  - Data rate: 0 GB/year
  - Power: 20 mW
  - Assumed: Estimated
- **Lander accommodation (same as entry, descent, and landing)**
  - Mass: 2.2 kg
  - Data rate: 5 GB/year
  - Power: 5 W
  - Assumed: Estimated
- **Other (5 kg)**
  - Mass: 19.4 kg
  - Data rate: 150 GB/year
  - Power: 12 W
  - Assumed: Estimated

* Numbers shown do not include 20% mass and power margin carried at the system level
* Any additional landing mass will be allocated to provide additional payload capacity.

4-lander mission can go anytime
The goal of a Lunar Geophysical Network is to understand the interior structure and composition of the moon.

- A variety of geophysical and compositional analyses of the Moon will enable researchers to determine the internal structure and composition of a differentiated planetary body.
- The next generation of geophysical measurements have to substantially improve on our current knowledge in order to make significant advances in science.
- Lunar geophysical science drives severe mission implementation needs:
  - Sophisticated instrument payload
  - 4 simultaneously operating nodes
  - Continuous seismometer operations
  - Long lifetime (2-6 years)
  - Farside placement

ILN Anchor Node:

<table>
<thead>
<tr>
<th>Mission Design Concepts</th>
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<tbody>
<tr>
<td>Brian Morse, Assistant Project Manager</td>
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ILN Anchor Node Pre-Phase A Major Activities:

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<th>CY09</th>
<th>CY10</th>
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ILN Anchor Node Lander Concept Evolution:

<table>
<thead>
<tr>
<th>Mission Concept of Operations</th>
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Resulting Lander Options:

<table>
<thead>
<tr>
<th>Lander Option</th>
<th>ASRG</th>
<th>Solar/Battery ASRG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Mass (Cruise/Lander) (kg)</td>
<td>1164/422</td>
<td>765/260</td>
</tr>
<tr>
<td>Generic max Landed Payload Support Mass (kg)</td>
<td>137</td>
<td>27</td>
</tr>
<tr>
<td>Max incl. Payload Mass for ILN (kg)</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Max incl. Payload Power for ILN (W)</td>
<td>19.8 day/7.8 night</td>
<td>Up to 76</td>
</tr>
</tbody>
</table>

- Both options are sized to perform ILN mission.
- ASRG option has additional mass and power margin for growth or other payloads.
- Solar-Battery option has significant total payload capacity for other Lunar missions.

Node Summary:

- ILN Anchor Node:
  - Project Milestone:
    - 2009-07: Test B (in funding)
    - 2010-07: Launch
  - Performance Status:
    - In Phase A:
      - July 2008: Technical and TIM w/on Instrument脸
      - September 2008: Initial Science
      - September 2009: Final Report
    - Market Research:
      - JPL, Ames, Sandia
      - Complete RFI

Launch and Cruise:

- Launch Options
  - 1 on Atlas V 401
  - 2 on Atlas V 411
  - 3 on Falcon 9 B1
  - 4 on Falcon 9 B2
  - 5 on Atlas V 401
  - 6 on Atlas V 411

Surface Operations:

- Ground/Space communications:
  - 14.5Gbps
  - 222Gbps
  - 960Gbps

Mission Status:

- Mission Baseline:
  - Launch and Cruise: July 2009
  - Surface Operations: December 2009

Launch Options:

- Launch Options:
  - 1 on Atlas V 401
  - 2 on Falcon 9 B1
  - 3 on Atlas V 411
  - 4 on Falcon 9 B2
  - 5 on Atlas V 401
  - 6 on Atlas V 411

Surface Operations:

- Ground/Space communications:
  - 14.5Gbps
  - 222Gbps
  - 960Gbps
ILN Anchor Nodes Current Status
Extended Pre-Phase A: Risk Reduction Activities

**Objective:**
Utilize extended formulation period to perform value-added work in an effort to reduce risk in the development and implementation phases of the project.

**Risk Reduction Activities Currently On-Going**
- Lunar Lander Test Bed: Hardware In the Loop (HWIL) testing with landing algorithms and thruster positions
- Propulsion: thruster testing in relevant environment, pressure regulator valve
- Power: battery testing
- Thermal: MBA analysis
- Structures: composite coupon testing, lander leg stability
- Avionics: reduced mass and power avionics box with LEON3 processor
- GN&C: landing algorithms
- Mole testing: JPL mole test more in lunar regolith simulant
- Seismograph task: analysis to inform the requirement for the number and location of sites

Lunar Lander Test Bed Overview

- Lunar Lander Robotic Exploration Test Bed initiated by MSFC
  - Provides a test environment for robotic lander test articles, components, algorithms, etc.
  - Implemented by Von Braun Center for Science and Innovation non-profit consortium
  - ILN anchor node project as first user has input into test bed requirements
- Development of MSFC cold gas test article
  - Test Bed team developed platform requirements with input from ILN project
  - RFP for structures and propulsion systems released in December 2008
  - Structure and propulsion system contract awarded in January 2009
  - Structure and propulsion system delivered in May 2009
  - Avionics integration completed
  - Test article provides ILN like thruster geometry and will implement a similar software environment for demonstration of technology
  - Serves as a test bed for flight development in certain areas (e.g. IMU interface, etc.)
- Test Status
  - Completed attitude control test
  - Vehicles acquired and demonstrated the ability to rotate and hold commanded orientation
  - Completed hardware-in-the-loop (HWIL) simulation testing
  - Cycling undergone high pressure system shows-out via HWIL simulations
  - Flight testing will commence once high pressure system performance is verified
- Next Generation
  - Activities underway to develop "warm" gas test article to begin longer duration testing in August 2010

Lander Multi-mission capability – Quick Look

ILN Anchor Node lander design is extensible to other science mission objectives

Information is Preliminary
Summary

- Both ASRG and Solar-Battery options are sized to perform the ILN mission
- Four ASRGlander mission is New Frontiers cost class and independently reviewed by NASA PA&E
- Significant concept development work has been performed
  - Concept is mature and accounts for necessary ILN accommodations
  - Majority of design is based on existing technology
  - Risks have been identified and a comprehensive risk reduction effort is underway
    - Significant portion of these activities nominally would be completed during Phase A/Phase B
    - Expenditures now on risk reduction activities increases confidence in the design and reduces cost for Phase A and Phase B
    - Cost estimates provided in the cost presentation have not been credited for these activities
- Lander designs are capable of supporting the selected SMD science mission based on results from Decadal Survey