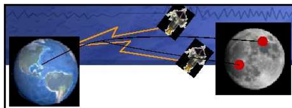
ILN ANCHOR NODES — NASA MSFC APL



International Lunar Network (ILN) Anchor Nodes

Planetary Decadal Survey
Inner Planets Panel
August 27, 2009

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Agenda

International Lunar Network Overview	G. Tahu
ILN Science	B. Cohen
Mission Design Concepts and Risk Reduction Tasks	B. Morse

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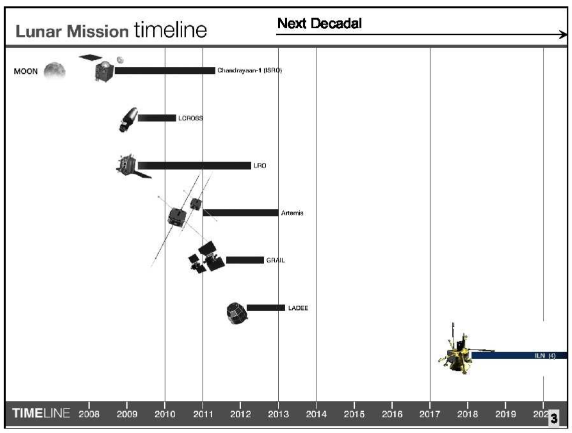

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What is… the International Lunar Network (ILN)?

- **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

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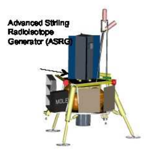
What is… the U.S. Anchor Node Project

- **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:**



4-node ASRG	Mission Concept	2-node Solar-Battery
$836M	Cost Estimate (FY10)	$607M
$890M	Cost Estimate (RY)	$650M
798/260 kg	Wet mass (cruise/lander)	1164/422 kg
Atlas V 401	Launch Vehicle	Falcon 9 B2
128 W	Power – cruise	95 W
115/115 W	Power - surface ops (day/night)	56/26 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.

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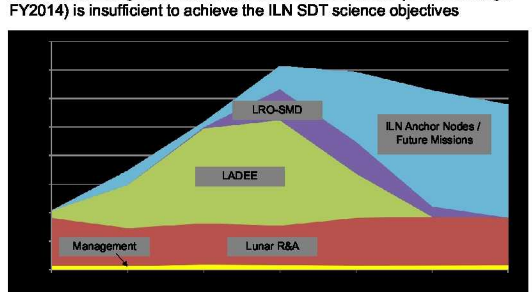
FY2010 Lunar Quest Program Budget

Lunar Quest budget for Anchor Nodes / Future Missions ($240M through FY2014) is insufficient to achieve the ILN SDT science objectives



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ILN U.S. Anchor Nodes Programmatics

- **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

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International Lunar Network Science

Barbara Cohen, ILN Project Scientist

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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 date

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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**

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Genesis of the Geophysical Network

- **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)**

Emplace a geo... rk to include, at a minimum, seismic and heat flow experiments ... l sensors, and new laser ranging retroreflectors. Such a prog... coordinated with those of other countries that are likely to incl... d missions in their space exploration strategies. The minimum ... nded sites should be four, more or less equidistantly ... g at least one farside site (no retroflector required). (SC

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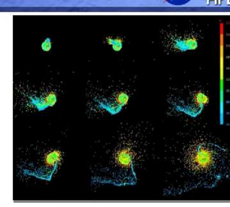
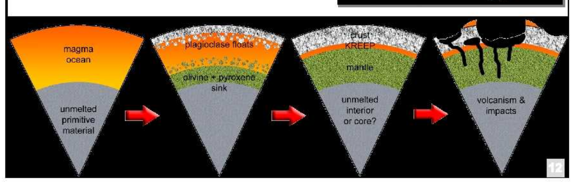
Lunar Interior Structure: The Theory

- **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 volcanism via mantle density overturn
  - Incompatible elements in KREEP layer
- **Redistribution by impact processes**





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Lunar Interior structure: Apollo Network

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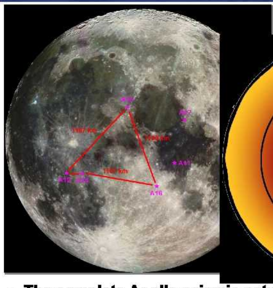

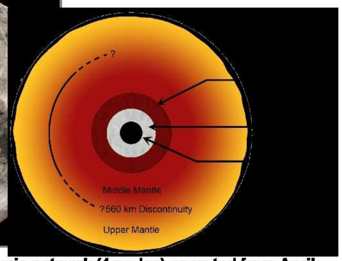

- The complete Apollo seismic network (4 nodes) operated from April 22, 1972 to Sept. 30 1977. Penetrated ~800 km deep.

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Lunar Interior Structure: Other Data

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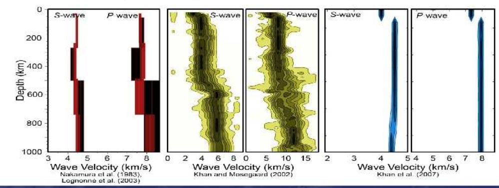
- Crust on near side is 30-40 km thick; far side is thicker (60 km). It has an anorthositic composition; lateral variations exist.
- Geochemical arguments hypothesize that the lunar mantle is layered and of a different composition than Earth's mantle
- Magmatism was most active > 3 Ga, therefore heat flow in the mantle was higher then
- There is probably a small (250-350 km diameter) core



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MANY Unresolved Science Questions

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- There are many unresolved science questions about the interior of the Moon, its evolution, and implications for other planets
  - Lunar Crust:
    - What are the vertical structural & thickness variations in the lunar crust (nearside
    - Are crustal structure changes gradational or are distinct domains present?
    - What is the global distribution of KREEP?
  - Lunar Mantle
    - How deep was the magma ocean, and how did it evolve (e.g., overturn,
    - convective mixing, etc.)?
    - Is there a Moon-wide ~500 km discontinuity? Is it structural or compositional?
    - What is the composition of the deep lunar interior?
    - Do crustal boundaries extend into the mantle?
  - Lunar Core:
    - What is the size/composition/state of the lunar core?
  - Moonquakes:
    - What are the locations, depth, and origins of the largest seismic events?
    - What causes deep moonquakes? Are there moonquake "nests" on the lunar fars
    - Are there attenuating (plastic) zones deep within the Moon?
- The next generation of geophysical measurements intended to directly detect a planetary core, to pro framework for interior models, and to understand lateral variations within a planet. *These objectives will substantially improve upon our current knowledge of planetary interiors.*

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ILN Science Definition Team (SDT)

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- 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 obtain the measurements
  - Define criteria for selection of the initial two sites
  - Identify technical challenges
  - To the extent that there is still 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*

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ILN Science Definition Team: Findings

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- 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 baseline of observations

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Science Baseline and Floor Definition

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- Geophysical Network Science Baseline Mission
  - Four stations, four instruments, concurrently active, lifetime of 6 years; farside 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

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Science Mission Drivers

ILN ANCHOR NODES · NASA · MSFC · APL

	SDT Report	Rationale
Number of Nodes	4 baseline 2 floor	4+ measurements for new independent science 2 nodes achieves reduced science objectives
Ops	Continual	Simultaneously receive seismic energy; capture diurnal and seasonal variations in heat flow/EM
Lifetime	6 year baseline 2 year floor	Cover tidal cycle; collect sufficient # of moonquakes
Landing sites	Global access	Need wide separation of all nodes (>2000km); characterize lateral variations
Launch Date	When needed to be part of network	Anchor larger network
Instrument payload	4 inst. baseline 1 inst. floor	Complementary measurements increase science, characterize lateral variations

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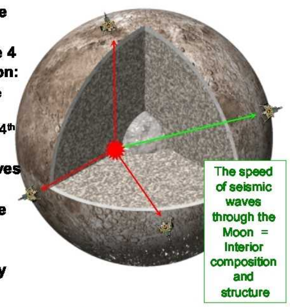
Number of Nodes & Operations

ILN ANCHOR NODES · NASA · MSFC · APL

- **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)**



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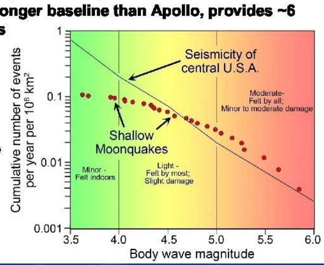
Lifetime

ILN ANCHOR NODES · NASA · MSFC · APL

- **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.**



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Landing Sites

ILN ANCHOR NODES · NASA · MSFC · APL

- **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/ research
- **Synthetic seismogram study will evaluate potential locations**
- **Site selection should be done with full community input, plus constraints from engineering**

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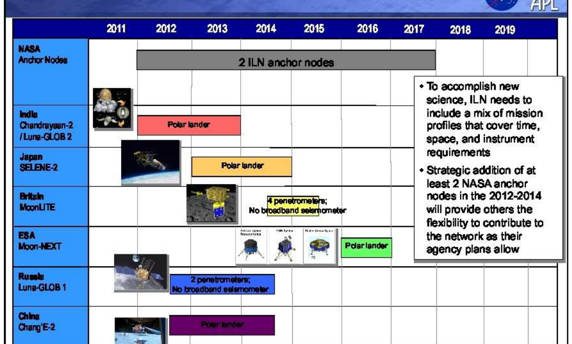
Launch Date

ILN ANCHOR NODES · NASA · MSFC · APL



- To accomplish new science, ILN needs to include a mix of mission profiles that cover time, space, and instrument requirements
- Strategic addition of at least 2 NASA anchor nodes in the 2012-2014 will provide others the flexibility to contribute to the network as their agency plans allow

4-lander mission can go anytime

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Notional Payloads

ILN ANCHOR NODES · NASA · MSFC · APL

Measurement	Instrument (Heritage)	Mass kg	Data Mb/day	Ave. Power W	Assumed Derived Requirements
Seismometry	Seismometer* (CNES Exomars, Netlander) Seismometer includes package with heaters, enclosure, foot pads	5	100	2.6	Vibration isolation 0.001–20 Hz Thermal stability ±5 deg Relative Time Acc ≤5 msec Continuous day/night operation
Heat Flux	Mole* (DLR HP3 Exomars) Mole includes package with electronics.	1.5	10	2.2	Regolith contact Vertical align during penetration Minimize thermal variations Operate during lunar night
EM Sounding	Electrometer, Magnetometers, langmuir probe (excluding booms, in lander accommodation	2.6	20	4.7	1.5 m boom 1 m mast for langmuir probe
Laser Ranging	Retro-reflector (LRO)	0.9	0	0	+/– 15 deg alignment to Earth
Guest Payload (extra instrument capacity)		2.2	5	3	
Lander accommodation (blankets, deploys, booms)		7.2			Booms/mast for EM, blankets, deployment mechanisms
Total		19.4	135	12	

- Numbers shown do not include 30% mass and power margin carried at the system level
- Any additional landing mass will be allocated to provided additional payload capacity.

Lander designed for ILN science by accommodating instruments that can provide required measurements.

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Summary: Lunar Network Science

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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

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International Lunar Network Anchor Nodes
Mission Design Concepts

Brian Morse, Assistant Project Manager

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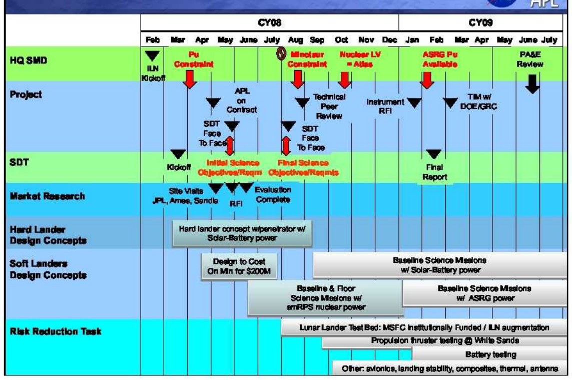
ILN Anchor Node Pre-Phase A Major Activities



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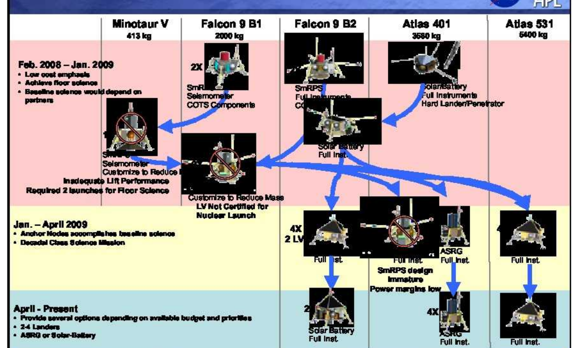
ILN Anchor Node Lander Concept Evolution



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Resulting Lander Options

Note: All mass and power figures include 30% growth margin	Lander Option: Solar/Battery	Lander Option: ASRG
Wet Mass (Cruise/Lander) (kg)	1164/422	796/260
Generic max Landed Payload/ Support Mass (kg)	157	37
Max Inst. Payload Mass for ILN (kg)	25	30
Max Inst. Payload Power for ILN (W)	19.5 day/7.8 night	Up to 74 Configuration dependent
Launch Options	• 1 on Taurus II Falcon 9 B1 • *2 on Falcon 9 B2** • 2 on Atlas V 401 with 952 kg excess capacity • 4 on Atlas V 531	• 2 on Atlas V 401 with 1684 kg excess capacity • *4 on Atlas V 401** • Other LVs require RPS qual.

**Lander was sized for this launch configuration.*

- **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**

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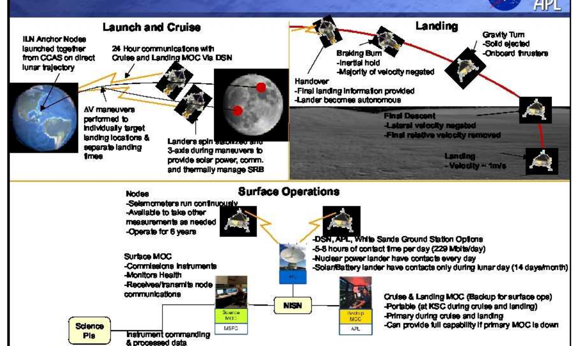
Mission Concept of Operations



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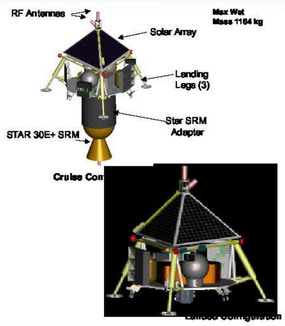
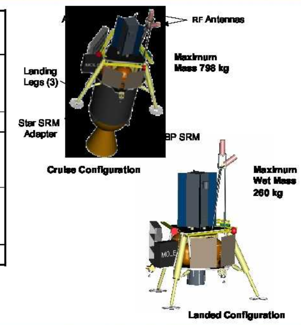
Solar-Battery Lander Design Concept

Power	•Solar Array Power for cruise & lunar day •Secondary Batteries for lunar night •Power System Electronics
Propulsion	•Bi-Propellant •100 lbf Descent DACS Engines (6) •6 lbf ACS DACS Engines (6) •2 Custom metal diaphragm tanks
Avionics	•Integrated Flight Computer and PDU
RF	•S-band •1 W RF transmit power •Antenna coverage for nearside or farside operations
GN&C	• Star Tracker (dual) • IMU • Radar Altimeter • Landing Cameras (2)
Structure	• Composite Primary Structure



ASRG Lander Design Concept

Power	•ASRG Primary Power Source •Power System Electronics •Primary Batteries
Propulsion	•Bi-Propellant •100 lbf Descent DACS Engines (3) •6 lbf ACS DACS Engines (6) •2 Custom metal diaphragm tanks
Avionics	•Integrated Flight Computer and PDU
RF	•S-band •1 W transmit power •Antenna coverage for nearside operations
GN&C	• Star Trackers (Dual head) • IMU • Radar Altimeter • Landing Cameras (2)
Structure	• Composite Primary Structure



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: WEB 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: test mole 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 nodes project as first user has input into test bed requirement
- **Development of MSFC cold gas test article**
  - Test Bed team developed platform requirements with input from ILN project
  - RFP for structure 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 basic GN&C control
  - Serves as a pathfinder for flight development in certain areas (e.g. IMU interface, cFE integration, etc.)

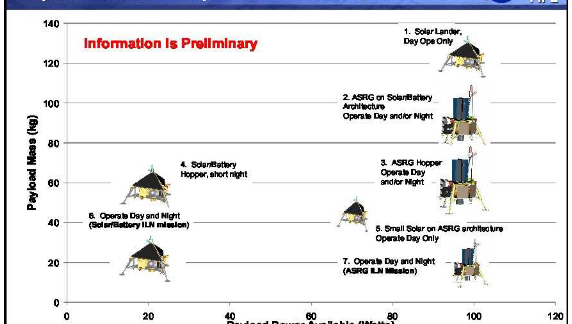
- **Test Status**
  - Completed attitude control test
    - Vehicle is suspended and demonstrates the ability to rotate to and hold commanded orientations
  - Completed hardware-in-the-loop (HWIL) simulation testing
    - Fixed vehicle fires thrusters in response to simulated sensor input
  - Currently undergoing high pressure system check-out via HWIL simulations
  - Flight testing will commence once high pressure 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

Robotic Lunar Lander Mission Capabilities
Payload Mass vs. Payload Power Comparison



Robotic Lunar Lander Mission Capabilities Assessed (Quick Look)

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ID # on chart 35	Lander Config	Core Lander Architecture	Day or Night?	Lifetime	Payload Mass (kg)	Payload Power (W)
1	Solar	Solar/Battery	Day	2 weeks to multiple months (polar/non-crater)	121 (Note 1)	100 (Note 1)
2	ASRG on large lander	Solar/Battery	Day and/or Night	up to 6 years	90 kg	100 W
3	ASRG Hopper	Solar/Battery	Day and/or Night	up to 6 years	65 kg	100 W
4	Solar/Battery Hopper	Solar/Battery	Day and/or Limited Night	10 days (Note 2)	60 kg (Note 2)	20 W (Note 2)
5	Small Solar	ASRG	Day	2 weeks to multiple months (polar/non-crater)	45 kg	70 W
6	ILN Solar/ Battery	Solar/Battery	Day and Night	6 years	19.2 kg	14.9 W
7	ILN ASRG	ASRG	Day and Night	6 years	23 kg	~100 W available
Not shown	Primary Battery/Fuel Cell	Solar/Battery	Day and/or Limited Night	10 hrs 100 hrs 4 weeks (Note 3)	118 kg 80 kg 50 kg (Note 3)	75 W 80 W 60 W (Note 3)

Note 1: Payload mass varies with payload power.
Note 2: Lifetime, payload mass, payload power and hop capability are variables depending upon battery and propellant mass.
Note 3: Lifetime, payload mass, and payload power are variables depending upon battery/fuelcell mass.

Information is Preliminary

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Summary

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- **Both ASRG and Solar-Battery options are sized to perform the ILN mission**
- **Four ASRG lander 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 increase 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**

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