NASA'S INTERNATIONAL LUNAR NETWORK ANCHOR NODES AND ROBOTIC LUNAR LANDER PROJECT UPDATE. Barbara A. Cohen[1], Julie A. Bassler[1], Benjamin Ballard[2], D. Greg Chavers[1], Doug S. Eng[2], Monica S. Hammond, Larry A. Hill, Danny W. Harris[1], Todd A. Holloway[1], Sanae Kubota[2], Brian J. Morse[2], Brian D. Mulac[1], and Cheryl L. B. Reed[2]. [1]NASA Marshall Space Flight Center, Huntsville AL 35812 (Barbara.A.Cohen@nasa.gov); [2]The Johns Hopkins University Applied Physics Laboratory, Laurel MD 20723.

Introduction: NASA Marshall Space Flight Center and The Johns Hopkins University Applied Physics Laboratory have been conducting mission studies and performing risk reduction activities for NASA's robotic lunar lander flight projects. Additional mission studies have been conducted to support other objectives of the lunar science and exploration community and extensive risk reduction design and testing has been performed to advance the design of the lander system and reduce development risk for flight projects.

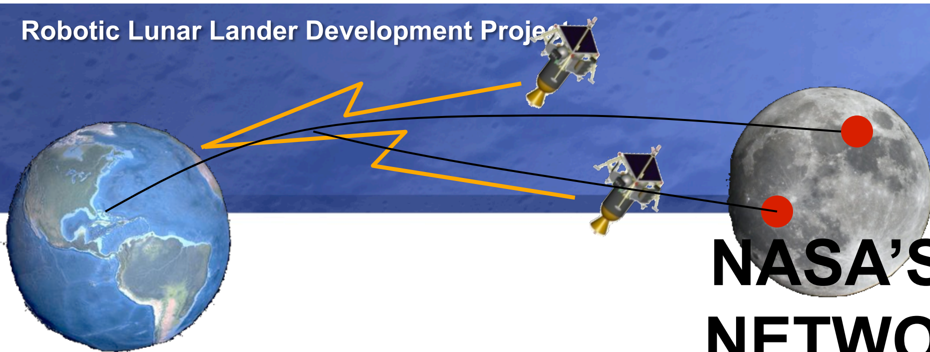
Mission Designs: Since 2008, the team has been supporting NASA's Science Mission Directorate designing small lunar robotic landers for diverse science missions. The primary emphasis has been to establish anchor nodes of the International Lunar Network (ILN), a network of lunar science stations envisioned to be emplaced by multiple nations. This network would consist of multiple landers carrying instruments to address the geophysical characteristics and evolution of the moon.

Based on the ILN studies, the team developed mission scenarios for two polar landers that share many common features: a Lunar Polar Rim mission rapid mission architecture for quickly demonstrating technology and landing on a polar rim, and a Lunar Polar Volatiles single point lander to study volatiles in a permanently shaded region.

Finally, the team worked with the Planetary Science Decadal Survey to develop a Lunar Polar Volatiles Explorer mission, consisting of a lander plus rover to study volatiles at multiple locations in a permanently shaded region. This mission uses a medium class lander and leverages from previous efforts on the Robotic Lunar Exploration Program 2 (RLEP-2) informed by new knowledge gained from the small lander class efforts.

Risk Reduction: During the pre-phase A studies for the ILN mission, lander subsystem technology risks were identified and prioritized based on technology readiness level (TRL) and commonality across multiple mission designs. The mass and power constraints of the lander system are key drivers for the risks. Risk mitigation activities to increase the TRL or reduce the development risk of key technologies were instigated, including high pressure propulsion system testing, structure and mechanism development and testing, long cycle time battery testing, thermal management system development and testing, and combined GN&C and avionics testing. The most visible elements of the risk reduction program are two free-flying autonomous lander test articles: a compressed air system with limited flight durations and a second version using hydrogen peroxide propellant to achieve significantly longer flight times and the ability to more fully exercise flight sensors and algorithms.

Uses for the Lunar Landers: For almost five years now, the MSFC/APL team has developed a flexible architecture of robotic lunar landers to envelop multiple mission scenarios. This architecture has both nuclear and solar array battery powered versions that interface to multiple launch vehicles depending on payload requirements, the number of landers desired, and available funding. The basic lander bus constitutes a transportation system that can be easily adapted to perform a number of different lunar science missions for NASA's SMD or lunar exploration missions for ESMD. The U.S. lunar science missions of the next decade, and their priority, will be determined by the in-progress Planetary Science Decadal Survey, and the lunar exploration missions are currently under study as defined by President Obama's new space policy and vision. For lunar robotic missions in general there is an intersection between science and exploration, and this robotic lander will satisfy requirements of the first of several surface missions envisioned to be implemented over the next five years. Combining missions in this way would constitute prudent use of NASA funds in an exciting partnership of two key Directorates (SMD and ESMD), and still provide the U.S. contribution to international ILN collaboration. Equally important, many of the robotic lander technologies to be demonstrated also have extended application to future robotic missions of other inner planet airless bodies, destinations of both SMD and ESMD.



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Contents

- **Lunar Lander Missions reported in this presentation**
- **Mission Concept Studies**
  - Mission Concept for launch, cruise, and landing
  - Small Lander class
  - Medium Lander class
- **Risk Reduction Status**
- **Summary**

Missions

4 missions presented today:

- **International Lunar Network (ILN) – anchor nodes for a geophysical mission**
- **Lunar Polar Rim (LPR) – rapid mission architecture for quickly demonstrating technology and landing on a polar rim**
- **Lunar Polar Volatiles Stationary (LPVS) – single point lander to study volatiles in a Permanently Shaded Region (PSR)**
- **Lunar Polar Volatiles Mobility (LPVM) – a lander with rover to study volatiles at multiple locations in a Permanently Shaded Region (PSR).**

Robotic Lunar Lander Development Project

Mission concept for launch, cruise, and landing – similar for all missions

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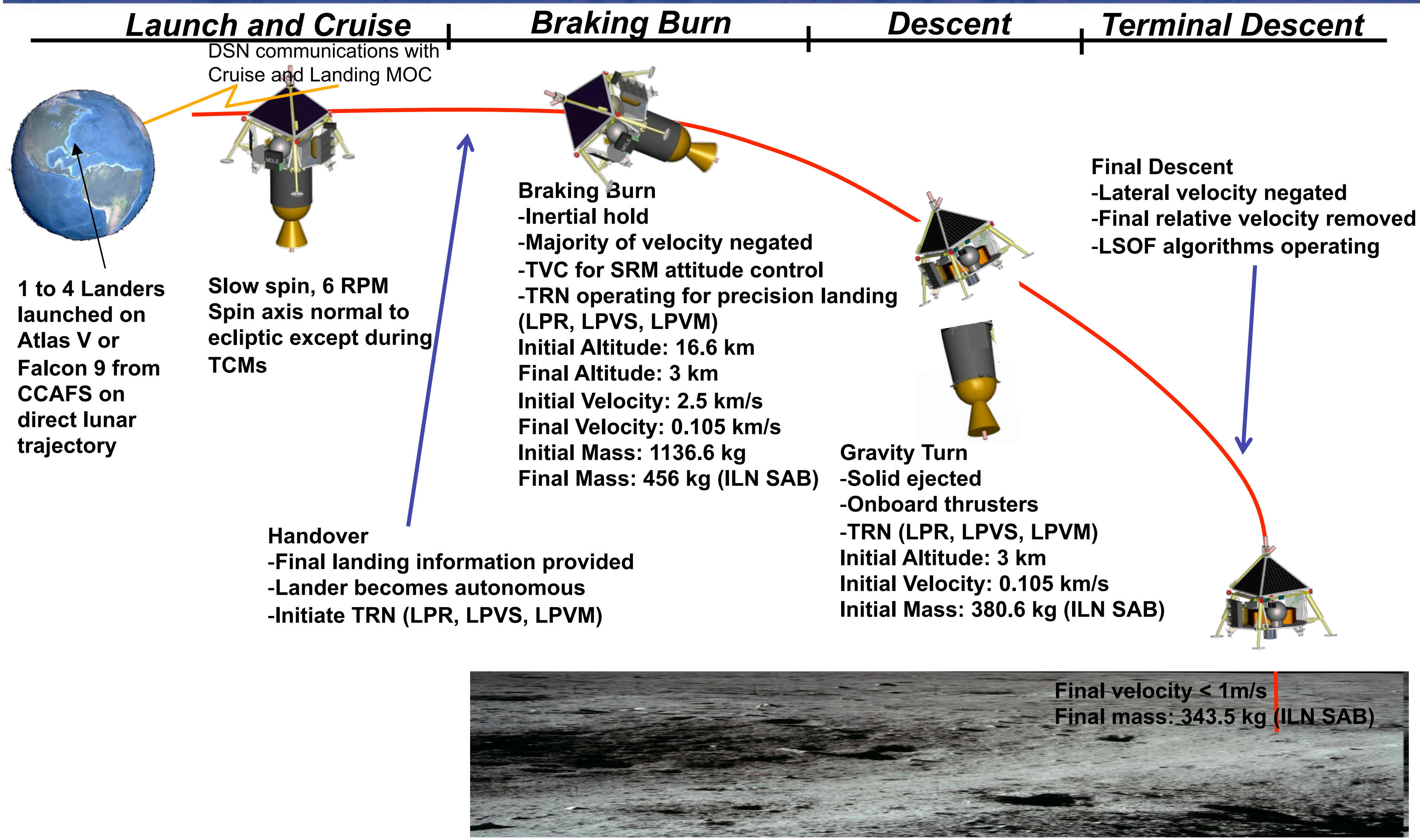

ILN Mission Attributes Derived from SDT Report

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- **NASA ILN anchor node mission**
  - In pre-phase A study with a technology risk reduction program since Spring 2008
  - A technical and costing review was conducted by NASA HQ in June 2009
  - Mission on hold awaiting Decadal Survey prioritization

Measure	Network Science Baseline	Science Floor
# of Nodes	4	2
Operational Duration	6 years	2 years
Instrumentation	Seismometer Heat Flow Measurements >3 m depths EM Sounding Laser Ranging	Seismometer
Seismic Measurements	Concurrent all nodes	Concurrent all nodes
Node Separation Distance	2000 km	2000 km
Placement	• Placed in each of the major terrains • Farside coverage desirable • Otherwise front side stations within 20º of limb	Stations placed relative to A33 moonquake nest hypocenter

ILN Notional Instrument Payload

Configuration	Measurement	Instrument *	Mass (kg)	Data (Mb/day)	Power (W)	Accommodation
Floor and Baseline	Seismometry	Seismometer (ExoMars)	5	100	2.6	Good surface contact Vibration isolation Thermal isolation
Baseline Only	Heat Flux	HP3 mole (ExoMars)	1.5	10	5.7 pk 0 nonop	Regolith contact to 3 m Initial vertical alignment Minimize thermal variations
	EM Sounding	Electrometer, magnetometer, langmuir probe (excl booms)	2.6	25	6.1 op 2 nonop	EM cleanliness Instrument separation from spacecraft
	Laser Ranging	Retroreflector (LRO)	0.46	0	0	+/– 15 deg alignment to Earth

* Representative instrument concepts used to develop lander concepts. Actual instruments are expected to be competed

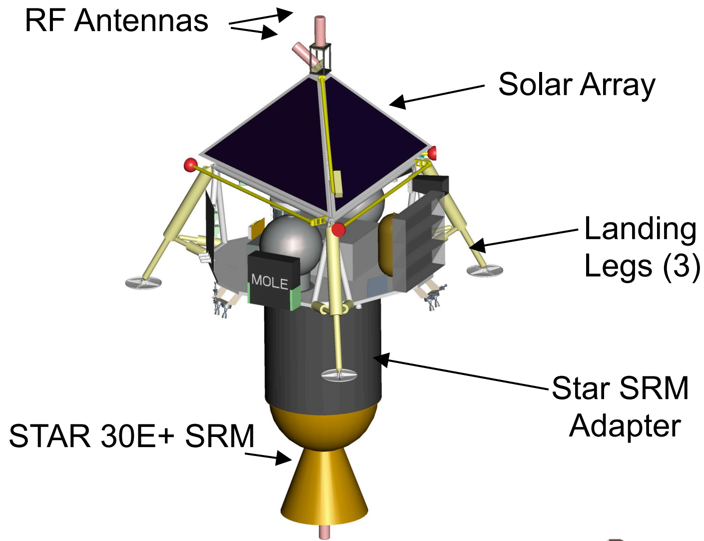
Note: Values in tables represent current best estimates and do not carry margins

Some synergy may exist among SMD, ESMD (surface plasma environment, hazard avoidance), and SOMD (comm sat, laser comm testing, etc.)

ILN Solar-Battery Lander Design Concept

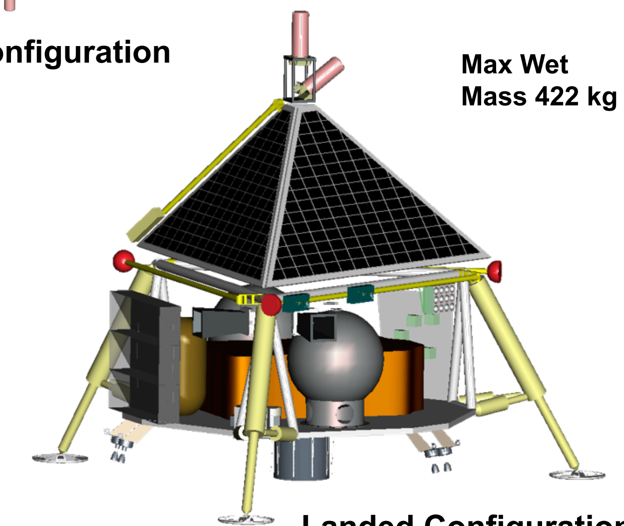
Power	•Solar Array Power for cruise & lunar day •Secondary Batteries for lunar night •Power System Electronics
Propulsion	•Bi-Propellant •445 N Descent DACS Engines (6) •27 N ACS DACS Engines (6) •2 Custom metal diaphragm tanks
Avionics	•Integrated Flight Computer and PDU
RF	•S-band •1 W RF transmit power •Antenna coverage for nearside or farside operations
GN&C	• Star Tracker (dual) • IMU • Radar Altimeter • Landing Cameras (2)
Structure	• Composite Primary Structure

Max Wet Mass 1164 kg



Cruise Configuration

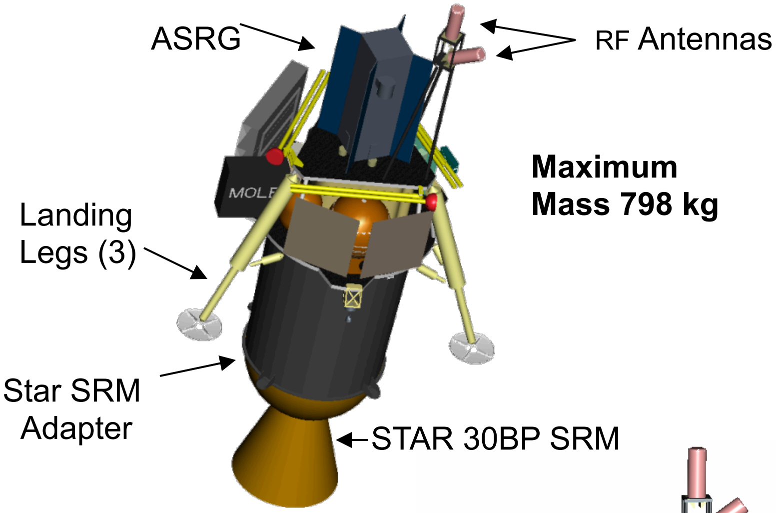
Max Wet Mass 422 kg



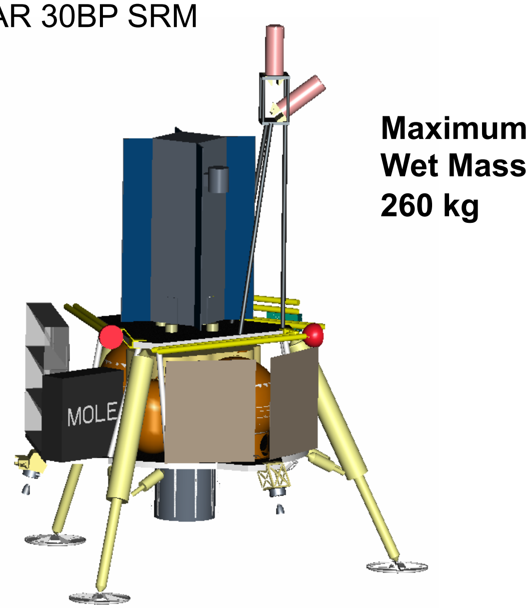
Landed Configuration

ILN ASRG Lander Design Concept

Power	•ASRG Primary Power Source •Power System Electronics •Primary Batteries
Propulsion	•Bi-Propellant •445 N Descent DACS Engines (3) •27 N 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

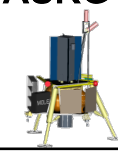


Cruise Configuration



Landed Configuration

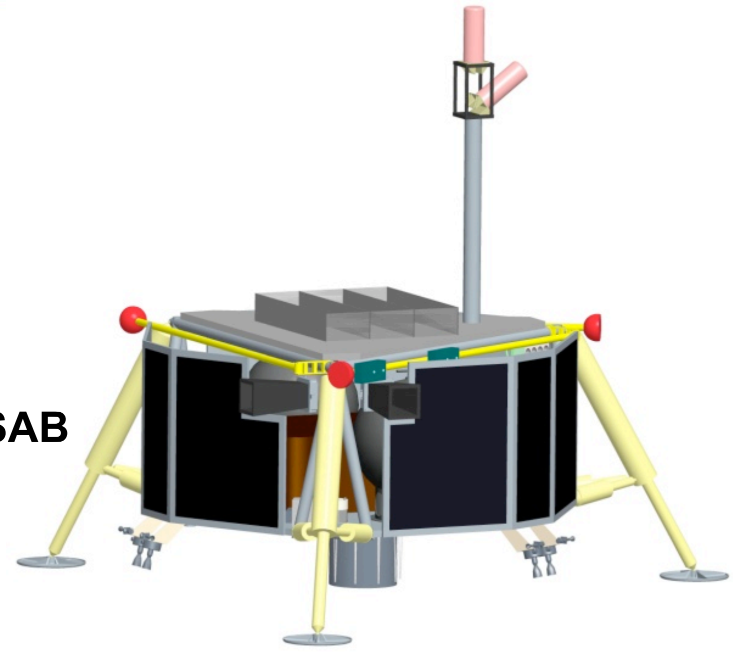
Comparison of ILN Lander Options

Note: All mass and power figures include 30% growth margin	Lander Option	
	Solar/Battery 	ASRG 
Wet Mass (Cruise/Lander) (kg)	1164/422	798/260
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	• *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

Lunar Polar Rim (LPR) – small lander



- **Lunar Polar Rim (non shaded region)**
- **Mission Goals**
  - Technology Demonstration – precision landing
  - Science Objectives
- **Single Solar Array – Battery Lander config from ILN SAB**
  - Switched solar array and radiator locations
- **Launch Vehicle: Delta II class or Falcon 9 class**
- **Lander Available <u>Payload</u> Mass / <u>Payload</u> Power driven by life requirement**
  - Operate lunar day only: 109kg / 25W
  - Operate lunar day and survive lunar polar night: 76kg / 20 (day) / 5W (night)
  - Operate lunar day and night for 6 years: 19kg / 12W (ILN, 372 hr night)

Lunar Polar Volatiles Mission Goals

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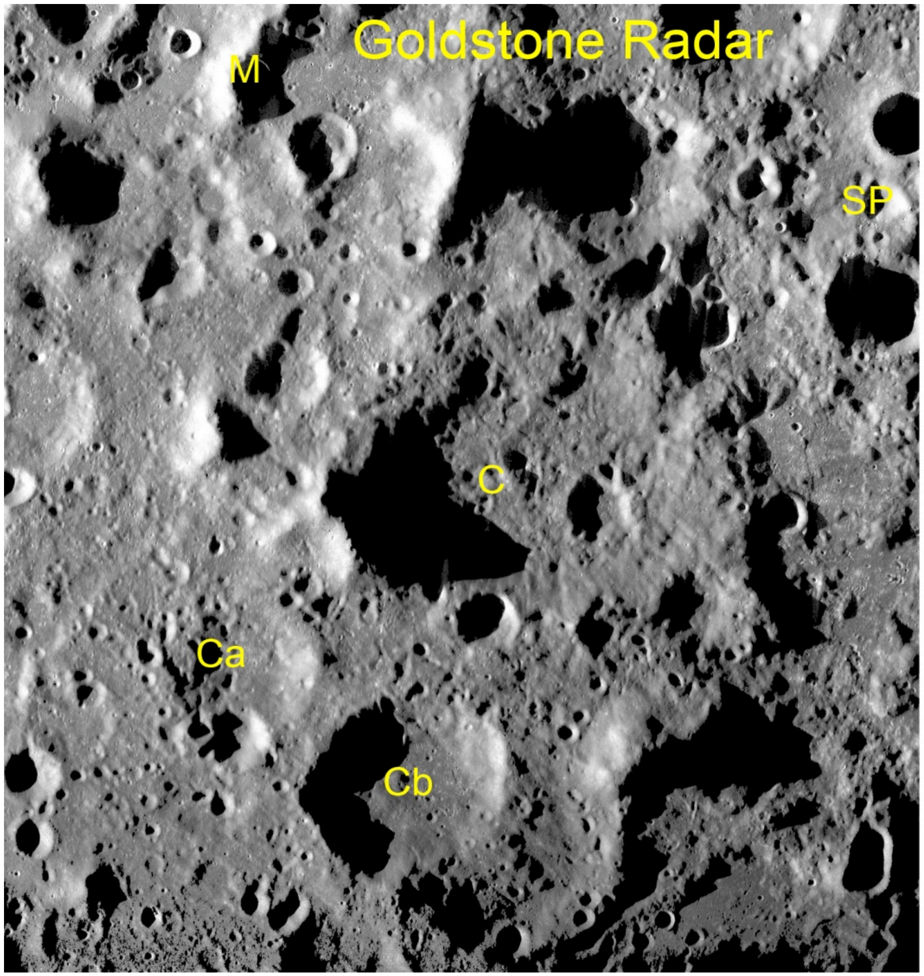
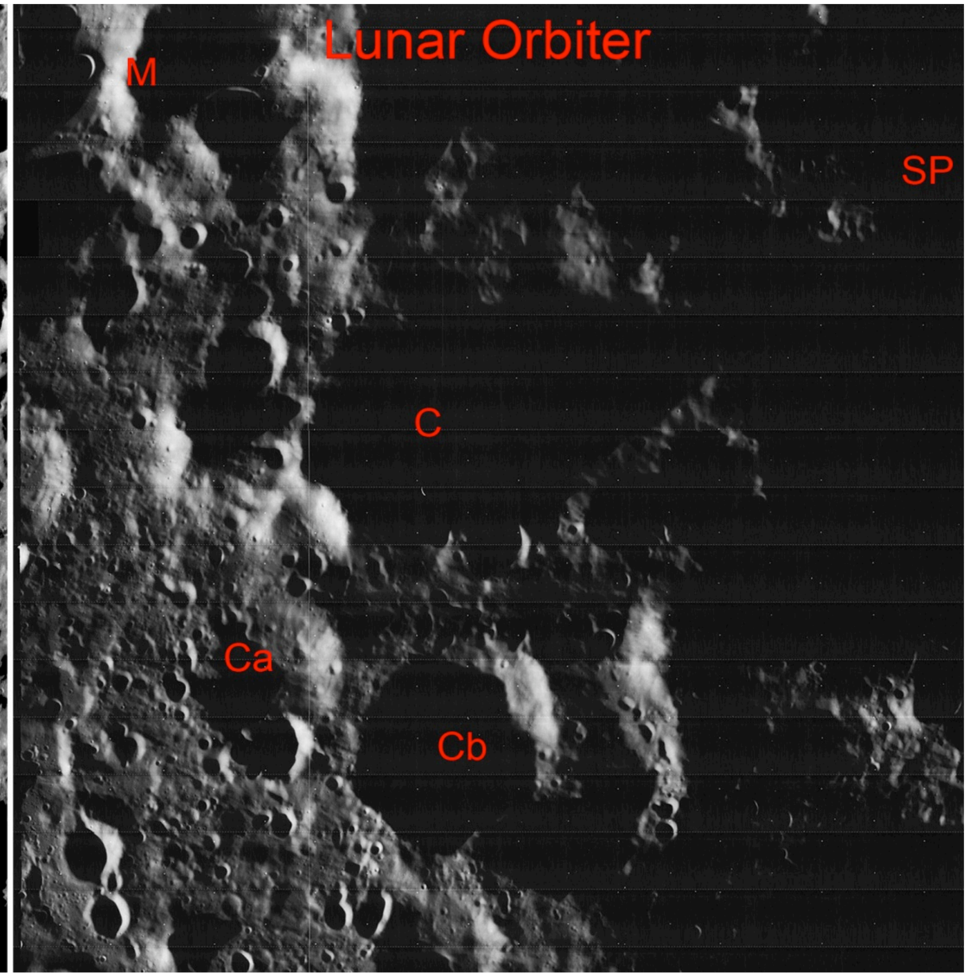
- **Mission Goal: Conduct a detailed inventory of volatile species and provide sufficient analysis to determine or greatly constrain the sources of polar volatiles and their nature**
- **Unique new science objectives:**
  – Determine the chemical composition, abundance and isotopic ratios (i.e. D/H) of volatiles cold-trapped in permanently shadowed regions of the lunar poles
  – Determine the near-surface vertical profile of the lunar polar deposits
  – Monitor the time-sensitive magnitude and variability of current volatile deposition from the exosphere and the environmental conditions that control this process
- **Mission overview**
  – **Single stationary polar lander (for LPVS) to permanently shadowed lunar crater.**
  – **ASRG powered and launched via Atlas V EELV. (Co-manifest compatible)**
  – **Land at a predetermined obstacle free site with 200m accuracy using TRN, no HDA**
  – **Payload to include drill (to 1-m in lunar surface) and sample analysis, spectrometry, ground penetrating radar and EM sounding.**
  – **Also provide seismometer to act as a single node of an ILN seismometry network.**
  – **Mission life provides 3 months of active drilling and 6 years seismometry.**
  – **Site selected to provide seven days per month communication direct to earth**

Shadowed from Sun but Visible from Earth





Radar illuminates view from earth

Orbiter depicts sunlit and dark areas

LPVS notional payload

MSFC APL

Lander Payload	*Objective*	*Mass kg*	*Power watts*
Drill & deployment mechanism	Recover regolith samples from depths of 1 m	39.0	108.3 – 520
Sample Camera	Imaging of drill sample	2.3	14
Sample Delivery System	Process core material for analysis	6.5	26
Mass Spectrometer	Determine the various volatile compounds	19.5	24 (48 peak)
Neutron Spectrometer	Determine the flux and energies of neutrons	1.3	2.3
Ground Penetrating Radar	Determine the depth profile of regolith to 10's of meters	5.0	6.5
Seismometer	Long-term monitoring of seismic activity	6.5	3.4

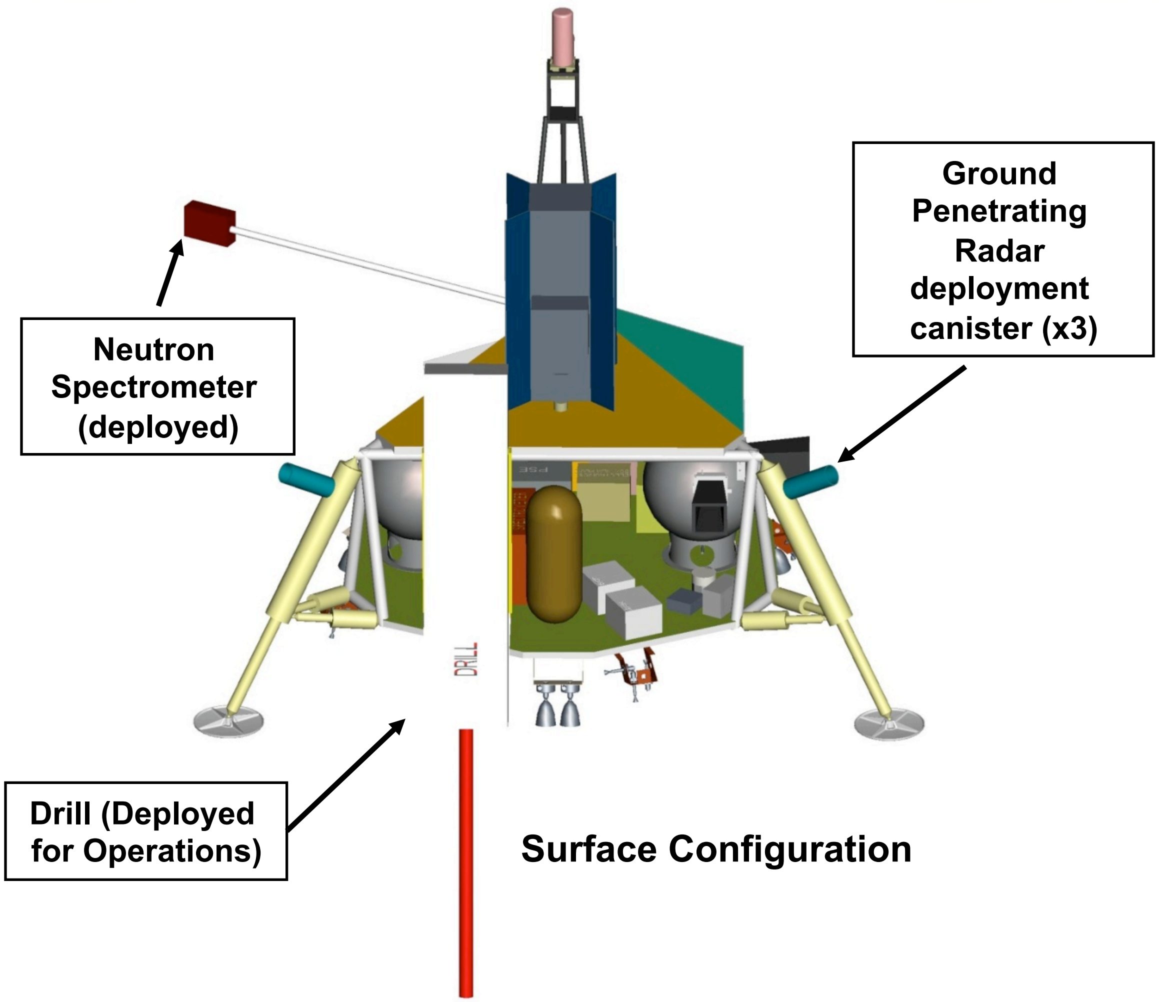
LPVS Lander Concept comparison

MSFC
APL

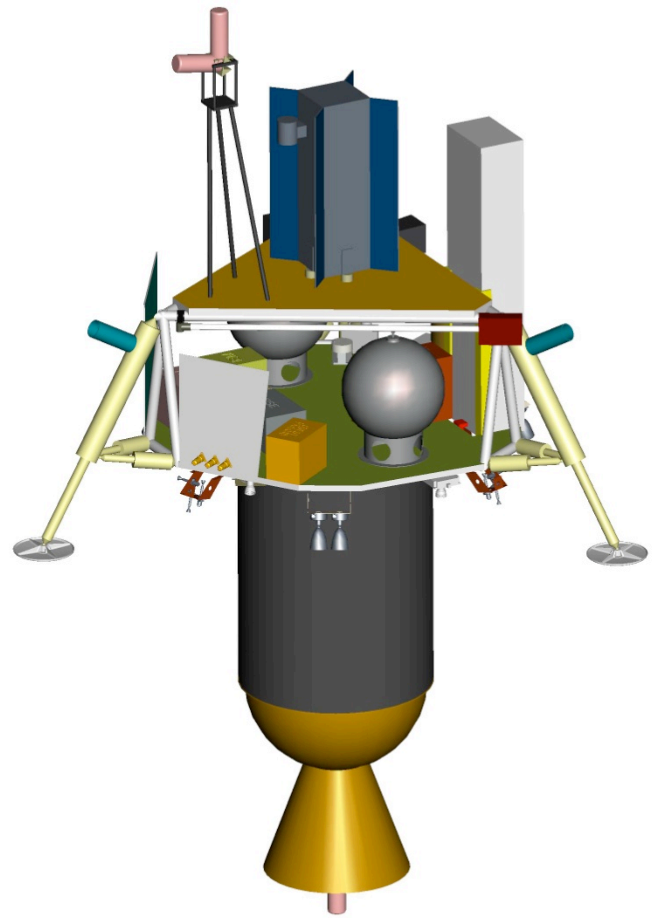
	ILN Design Approach	Polar Volatiles Mission Stationary
Structures	• Composite Primary Structure	• Composite Primary Structure
Deployments	•Seismometer, EM booms, Mole	• Seismometer, NS boom, drill and sample collection
Power	•ASRG Primary Power Source •Power System Electronics •Primary Batteries	• ASRG • Secondary Batteries to support Drill and landing • Power System Electronics
Thermal	•Isolated WEB, variable link to Radiator	• Isolated inner structure, variable link to Radiator
Propulsion	•Bi-Propellant, custom tanks •445 N Descent DACS Engines (6) •27 N ACS DACS Engines (6)	•Bi-Propellant, custom tanks •445 N Descent DACS Engines (6) •27 N ACS DACS Engines (12) – precision landing
Avionics	•Integrated Flight Computer and PDU	• Upgrade to faster Maxwell 750 processor for precision landing TRN • Separate PDU
RF	•S-band •1 W transmit power •2 kbps uplink, 100 kbps downlink capable on surface	•S-band •1 W transmit power •2 kbps uplink, 100 kbps downlink capable on surface
GN&C	• Star Trackers (Dual head), Landing Cameras (2) • IMU, Radar Altimeter	• Star Trackers (Dual head), Landing Cameras (2) • IMU, Radar Altimeter • TRN added to meet precision landing in earth shine • Increased TVC accuracy on SRM
Software	• ILN Baseline	• More complex autonomy for drill, TRN processing for precision landing
Msn Ops	• Long duration autonomous ops	• Shorter duration, complex tasks
Launch Vehicle	• 1-4 landers on Falcon 9 or Atlas V 401 -511	• Single lander on Atlas V 401 (ASRG mission)

Deltas highlighted

LPVS Lander Configuration

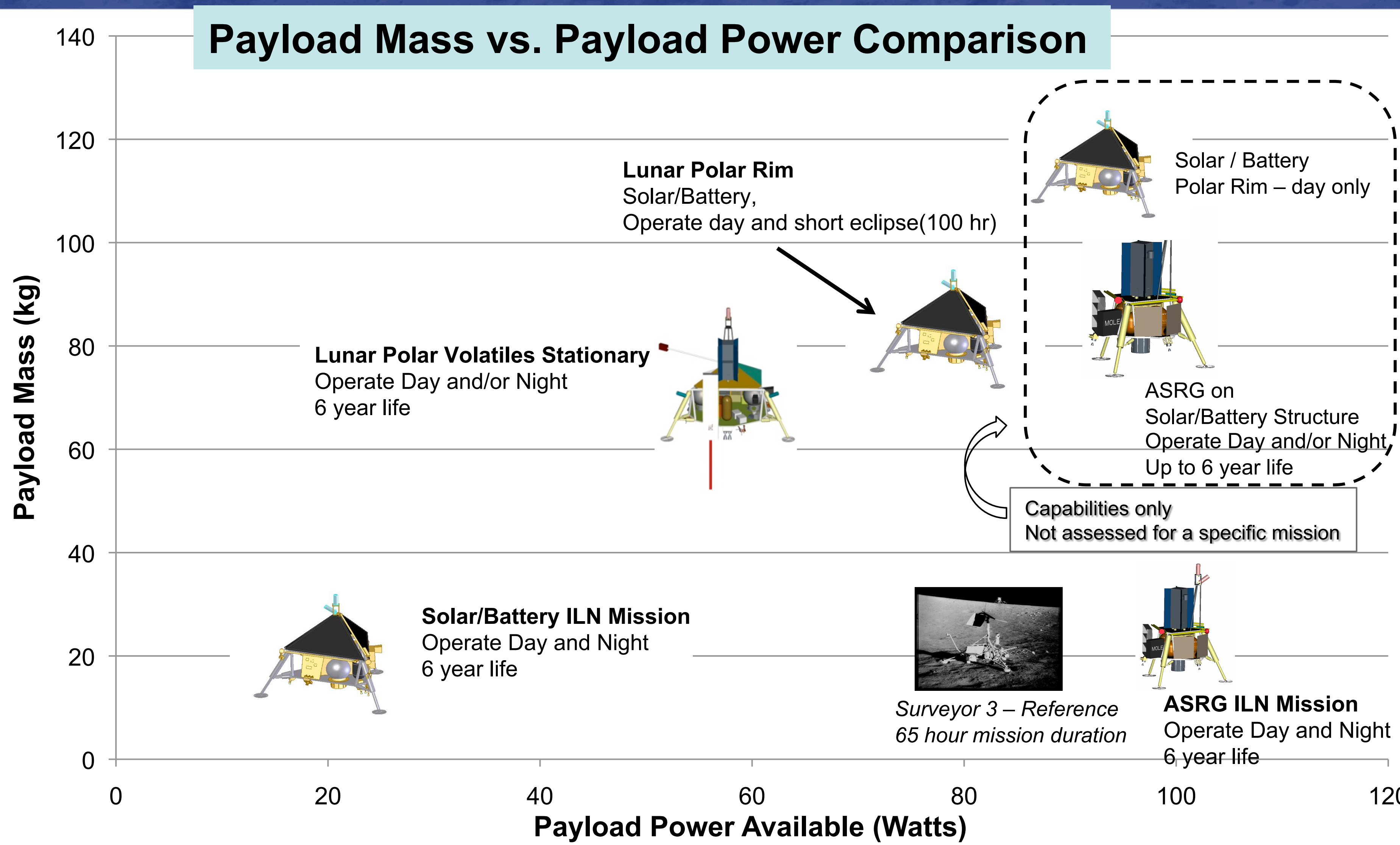


Surface Configuration



Cruise Configuration

Robotic Lunar Lander Summary (2008-2010)
Small lander comparision



LPVM

- **Mission Goal: Similar to the Lunar Polar Volatile stationary / single site "small" lander with additional goal:**
  - provide mobility to acquire knowledge about spatial distribution of volatiles
- **Unique science objectives: Same as LPVS with addition:**
  - acquire knowledge about spatial variation of volatiles
- **Mission overview**
  - **Single polar lander with mobility to permanently shadowed lunar crater.**
  - **ASRG or battery powered and launched via Atlas V EELV. (Co-manifest compatible)**
  - **Land at a predetermined obstacle free site with 200m accuracy using TRN, no HDA**
  - **Payload to include drill (to 1-m in lunar surface) and sample analysis, spectrometry, ground penetrating radar and EM sounding.**
  - **Also provide seismometer to act as a single node of an ILN seismometry network (ASRG version only).**
  - **Site selected to provide seven days per month communication direct to earth**

Lunar Polar Volatiles – Mobility

- **Notional Payload**

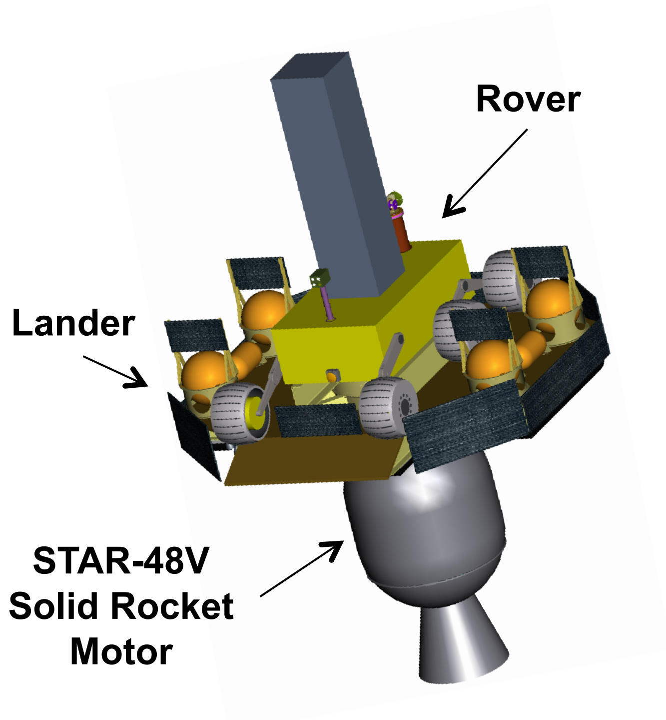
Lander Payload	*Objective*	*Mass kg*	*Power watts*
Rover Neutron Spectrometer	Lateral distribution of H	.7	2.3
Downhole Neutron Spectrometer	Vertical distribution of H	.8	2.9
Downhole Imaging	Imagery of volatiles	0.3	1
Gas Chromatograph Mass Spectrometer	Determine species of volatiles	13	10.4 (avg) 47
Drill & Sample Acquisition		41.6	98
Sample Delivery		8.5	34
X-ray Diffraction	Mineralogy	.9	12
Ground Penetrating Radar	Subsurface geological	3.5	8
Exospheric Mass Spec	Measure components of exosphere	6.5	26
Surface imaging	Geological context	1.1	11

Flight System

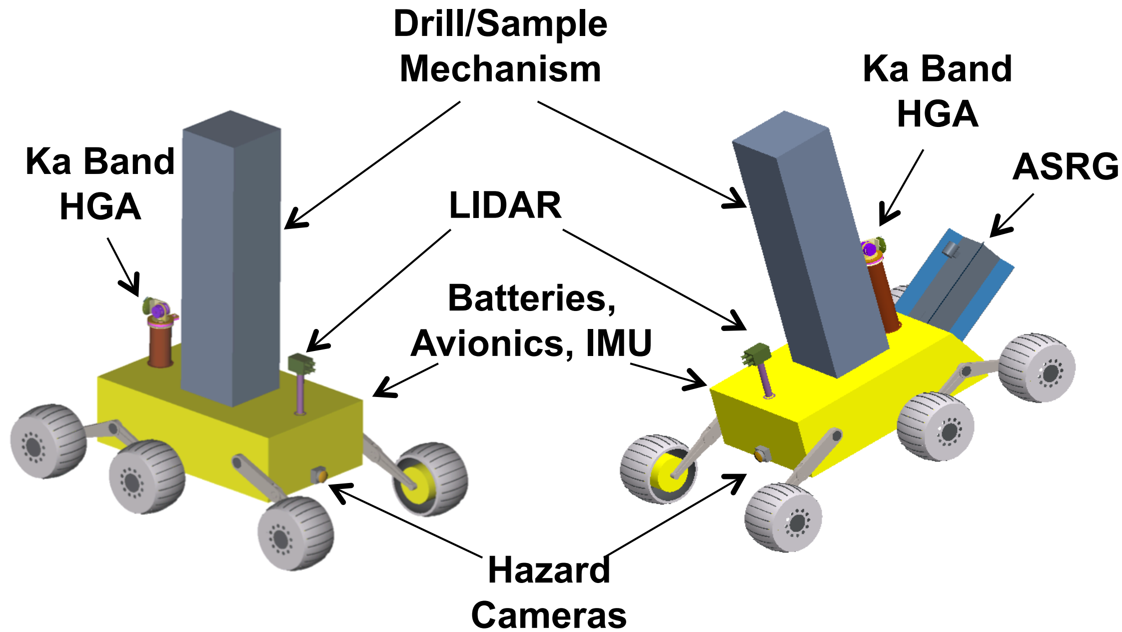
Structures / Mechanical (Battery Mission)

•Mobility with notional instruments for volatile interrogation requires larger mass to the surface than provided by the small landers.

•An RLEP 2 concept (developed by this team) with updated knowledge gained by this team from the small lander efforts.



Integrated Flight System



Battery Rover

ASRG Rover

Risk Reduction

Incremental Development Approach for Flight Robotic Lander Design: Phase 1 (Cold Gas)

MSFC NASA APL

Robotic Lander Testbed - Cold Gas Test Article (Operational)

- Completed in 9 months
- Demonstrates autonomous, controlled descent and landing on airless bodies
- Emulates robotic f**light** lander design for thruster configuration in 1/6th gravity
- Incorporates **flight** algorithms, software environment, heritage avionics, and sensors
- Gravity cancelling thruster provides for reduced gravity operations that can vary with throttling
- Flight time of 10 seconds and descends from 3 meters altitude
- Utilizes 3000psi compressed air for safety, operational simplicity, and multiple tests per day
- 3 primary and 6 ACS thrusters

Accomplishments

Fully Functional, Flown >150 times

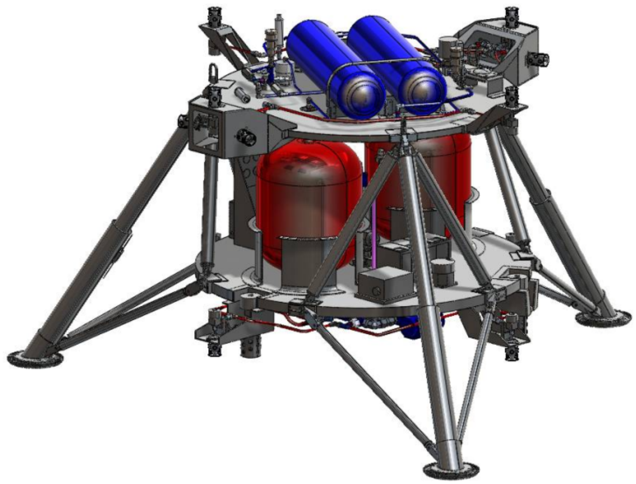
Upgraded with flight-like algorithms

Incremental Development Approach for Flight Robotic Lander Design: Phase 2 (Warm Gas)

MSFC NASA APL

Warm Gas Test Article (Summer 2010) adds to Cold Gas Test Article Functionality:

- Demonstrates terminal descent phase autonomous controlled
- Began WGTA September 2009 ; Critical Design Review March 2010
- Designed to emulate Robotic **Flight** Lander design sensor suite, software environment, avionics processors, GN&C algorithms, ground control software, composite decks and landing legs
- Longer flight duration (approx. 1 min) and descends from 30 meters to support more complex testing
- Can accommodate 3U or 6U size processor boards.
- Incorporates Core Flight Executive (cFE) which allows for modular software applications
- 12 thruster ACS configuration. Option to only fire 6 ACS thrusters. Provides capability to support testing of hazard avoidance or precision landing algorithms. Emulates pulse or throttle system.
- G-thruster can be set to different g levels between 1 g to zero g for descent. Therefore, can be used to emulate any airless body for descent.



Accomplishments

Mechanical Design Complete, Fabricating elements

GN&C Framework S/W delivered, 2nd build in test

Testing begins Summer 2010

Flight Propulsion System Risk Reduction Status

MSFC APL

Light-Weight Thruster Hot-Fire Tests for Robotic Lunar Lander

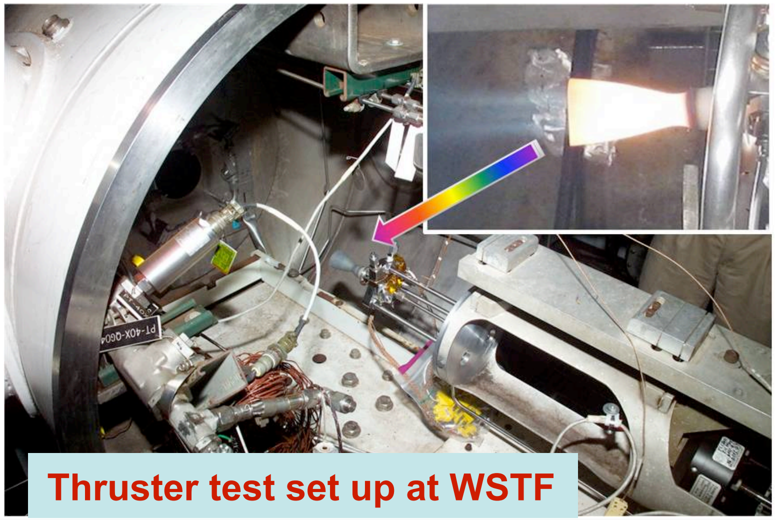
❖ **Objective:** **a**) Leveraging DOD thruster technology; **b)** Test both 445 N descent and 27 N ACS thrusters in vacuum to assess performance, thermal, and combustion stability.

❖ **Accomplishment:**

– Successfully completed a matrix of 12 hot-fire tests on 445 N thruster in Sept., 2009 at WSTF

– Evaluated 445 N thruster characteristics in relevant environment with a representative full mission flight profile spanned 995 seconds.

– Test plan for 27 N ACS thruster to be conducted in July, 2010.



Thruster test set up at WSTF

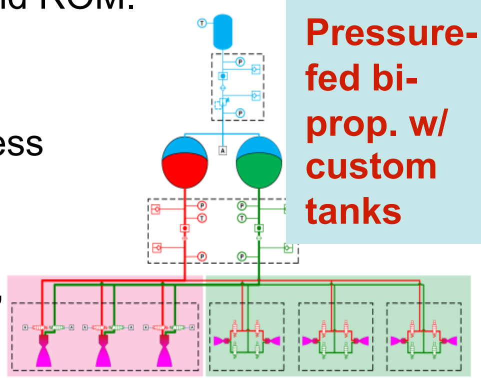
Propulsion Concept Assessment

❖ **Objective:** **a**) Evaluate propulsion design concept; **b)** Independent assessment on propulsion technology maturity, work schedule, and ROM.

❖ **Accomplishment:**

– Verified propulsion design concept, technology readiness level, and cost in July, 2009

– Wide participation of propulsion industry (Aerojet, AMPAC, Orion Propulsion, and PWR) in concept study.



Pressure-fed bi-prop. w/ custom tanks

High-Pressure Regulator Characterization

❖ **Objective:** MSFC in-house evaluation and characterization of pressure regulator operated at high blow down ratio for light-weight propulsion system

❖ **Accomplishment:**

– Received the regulator test article.

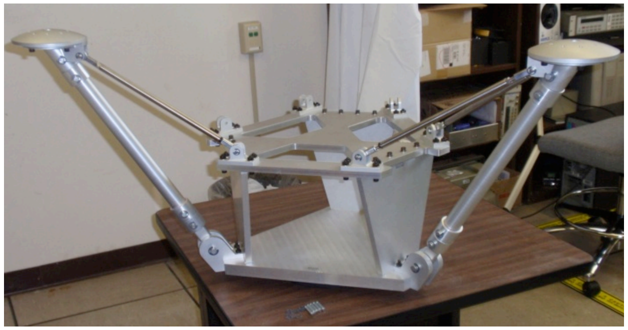
– Obtained all components and instrumentation for test setup.

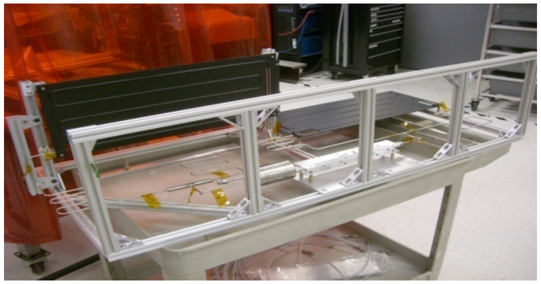
– Completed test plan & documentation

10K psi regulator

Other Risk Reduction Status

- **GN&C**: Validation of landing algorithms with simulations and HWIL
  - Testing Optical velocity estimater
  - Running Monte Carlo simulations
- **Structures**: Composite panel fabrication and testing, lander leg stability testing, star motor vibe test
  - Coupon testing complete
  - Starting WGTA Panel fabrication
  - Rigid body stability testing complete – Good correlation with analysis
  - Flexible/nonlinear test article and fixtures in assembly
  - Star motor adapter design complete, finalizing fabrication subcontract





- **Thermal**: Variable heat transport and lunar heat rejection testing
  - Completed fabrication of Loop Heat Pipe assembly Finalizing test Plans
- **Power**: Thermal and life battery testing
  - Batteries on order
- **Avionics:** Testing a low power, high speed communications, and large data storage processor
  - Design Complete. Printed wiring boards in fabrication
- **Ground Systems:** Portable Mission operations Centers **(**mini-MOCs) for control of WGTA
  - Mini-MOCs assembled. Working Screens and networking configurations

Summary

- ILN mission on hold awaiting Decadal Survey results
- Lander bus design has been refined and is suitable for multiple mission scenarios
- Recent knowledge and experience used to inform and update RLEP2 lander options for medium lander class
- A comprehensive risk reduction effort is underway and is producing results
- NASA's new direction in space exploration may present an opportunity for a robotic lunar lander to support exploration objectives